THE IMPACTS OF WILDFIRE AND MOUNTAIN PINE BEETLE DISTURBANCE ON WOOD BUDGETS, STABILITY AND RELATED SEDIMENT STORAGE IN LOW-SEDIMENT SUPPLY STREAMS OF THE OKANAGAN BASIN

by

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Abstract

This thesis presents the Large Woody Debris (LWD) budgets and related sediment dynamics of 12 headwater streams in the Okanagan Basin of British Columbia. The study streams include 3 wildfire (from the recent Okanagan Mountain Park Fire in 2003) sites and 3 control sites in the Interior Douglas-fir (IDF) biogeoclimatic zone, and 3 recent Mountain Pine Beetle (MPB) infestation sites and 3 control sites in the Montane Spruce (MS) zone. The wood budget components were quantified based on repeated annual wood surveys, and represent the first wood budgets produced in the literature. Wildfire was found to significantly increase annual wood recruitment by more than an order of magnitude over undisturbed or control streams. MPB had not significantly increased LWD recruitment, but is expected to increase over the coming decades. Both of the riparian disturbances had shifted the size distribution of recruits to larger wood sizes. Our analysis confirms that the matrix of relative wood size presented by Hassan et al. (2005) is a good predictor of wood stability and export. Wood stability was in turn a primary determinant of wood function and the role of wood in sediment storage.

Wood in the study streams stored between 0% and 90% of the sediment in the channels. Sediment stores increased with increasing functional wood loading. This highlights an important role of LWD in sediment storage in spite of large variations. However, in contrast to literature on the role of LWD in supply-rich streams, LWD in our supply-limited streams was found to have no statistical relationship to sediment diversity and was found to be less effective at causing sediment fining. We suggest that LWD-related sediment storage sites in supply-limited streams replace rather than supplement alluvial storage sites as they would in sediment-supply rich streams, and thus do not increase sediment diversity. Furthermore, LWD is a less important

roughness element in these step-pool systems compared to pool-riffle systems, and is thus not effective at causing sediment fining under step-pool conditions.

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List of Symbols and Abbreviations

IDF	Interior Douglas Fir
LWD	Large Woody Debris
MS	Montane Spruce
MPB	Mountain Pine Beetle
D_{50}	Median Grain Size
τ_o	Shear Stress

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Dedication

For my ever patient, ever loving parents. You are my best friends and my biggest fans.

Although perhaps a dubious honour, this one's for you.

Chapter 1: General introduction

Streams and rivers with forested riparian zones are intimately linked to the surrounding forests. Living trees stabilize banks and soil (e.g., Greenway, 1987; Thorne, 1990; Abernethy and Rutherford, 2000), contribute allocthonous inputs (Wallace and Eggert, 1997; Richardson, 1991), shelter streams from direct sunlight (e.g., Larson and Larson, 1996), and on a larger scale alter the hydrology of the watershed (e.g., Hibbert, 1967; Bosch and Hewlett, 1982). When dead trees enter fluvial systems, they play a primary role in stream ecology and channel morphology, continuing the link between riparian and aquatic communities. Large Woody Debris (LWD) is a primary agent in determining habitat quality in streams by forming pools, riffles, steps and hydraulic jumps, storing sediment and significantly altering channel hydraulics (e.g., Nakamura and Swanson, 1993; Faustini and Jones, 1996; Curran and Wohl, 2003).

The role of LWD in determining channel morphology is complex and is influenced by channel type and riparian condition, as well as the characteristics of the wood itself. Small, supply limited headwater streams respond very differently to LWD inputs than larger, transport limited channels. Furthermore, methods of wood input and transport differ significantly in smaller channels relative to larger ones. However, larger channels have historically received more research attention than their headwater counterparts, despite recent research emphasizing the important ecological role of headwater streams (e.g., Gomi et al., 2002; Richardson and Danehy, 2007). Superimposed on this variability, natural and anthropogenic disturbances change recruitment patterns and LWD characteristics, adding another layer of spatial and temporal complexity. As a result of this complexity, research attempts to quantify LWD dynamics and functions are persistently limited by the difficulty of trying to quantify stochastic processes highly influenced by episodic events such as riparian disturbance or major floods, based on one-time in-channel measurements.

Nonetheless, over the past several decades research has quantified dynamics of LWD recruitment and input (e.g., Keller and Swanson, 1979; Bragg, 2000, May and Gresswell, 2003; Warren and Kraft, 2008), in-stream interactions with hydraulics and sediment and resultant morphological features (e.g., Buffington and Montgomery, 1999a; May and Gresswell, 2004; Chen et al., 2008; Warren and Kraft, 2008; Klaar et al. 2011), and controls on wood stability and transport (e.g., Braudrick et al., 2000). Benda et al. (2003) proposed a method of quantifying wood dynamics through the use of wood budgets. However, this methodology has never been fully applied and there is a persistent need to develop wood budgets for a range of systems, and to quantify their response to disturbance and basin characteristics. Significant questions remain regarding the impacts of spatial variability and disturbance regime on wood recruitment and budgets. Additionally, sediment dynamics in headwater streams are themselves not yet adequately understood, and understanding the role of LWD as a geomorphic agent in these systems requires research that investigates the implications of low sediment supply and addresses the impacts of riparian disturbance. Although LWD has been shown to significantly influence sediment dynamics is supply-rich streams (e.g., Buffington and Montgomery, 1999a), research is needed to verify whether these interactions can be generalized to sediment-supply limited streams.

The research presented in this thesis addresses two research gaps related to quantifying wood dynamics and the sedimentological role of LWD. By making use of a unique five year record of repeated wood surveys in a range of low order, sediment supply limited forested streams in the Okanagan Basin, wood budgets (as per the framework developed by Benda et al., 2003) are developed and reported in detail. The relationship between wood loading and sediment storage and diversity is quantified. The role of LWD in determining sediment storage, diversity and fining in these low-sediment supply streams is contrasted with previously published data on the interaction of wood and sediment in high sediment supply streams in Alaska and the Olympic Peninsula (Buffington and Montgomery, 1999a). The impacts of wildfire and Mountain Pine Beetle (MPB) infestations on these LWD dynamics are reported to address concerns over the ecological impacts of these widespread and pervasive southern British Columbia (BC) forest disturbances.

This research provides detailed quantifications of wood storage and wood budgets that are rare if not absent in the existing literature. Furthermore, it contributes to a recent and important surge in research quantifying the dynamics and importance of wood and sediment in small, low sediment supply streams where sediment-discharge and magnitude-frequency relationships are complicated by the interacting effects of large roughness elements, armoured beds and well developed bed forms (Benda et al., 2005; Hassan and Zimmermann, 2011). Additionally, this research supports a growing body of research concerning natural forest disturbances.

1.1 Research objectives and approach

This research is part of a long term study into LWD dynamics in a disturbance context established in 2004 and 2005, which gathered data from 12 streams with a range of morphological and riparian conditions in the Okanagan Basin, BC. We incorporated data from the first five years of the study to build complete wood budgets for the study streams in question, and we reported on the findings of an in-depth sedimentological survey of the study streams. In particular, we emphasized the importance of external riparian and geomorphic controls. In the two following chapters, we answered the following questions:

1) What are the wood budgets of the study streams, how do they vary with riparian disturbance and condition and what patterns exist in the different components of the budgets?

2) How does LWD alter sediment dynamics in low-sediment supply Okanagan streams in terms of sediment storage volume, diversity, and substrate fining? How do these LWD-sediment interactions compare and differ from those in high-sediment supply streams?

Both of these questions are answered in the subsequent two chapters, and a general discussion is provided at the end of the document to relate the findings and provide context to the management implications of our findings.

Chapter 2: Wood budgets of mountain streams in the Southern Interior of British Columbia and their response to wildfire and Mountain Pine Beetle infestation in riparian zones

2.1 Context and background

Over the last fifty years, Large Woody Debris (LWD) has been increasingly recognized as a morphological, biological and chemical agent in aquatic ecosystems. It can affect a wide range of morphological attributes, from changing channel hydraulics (Curran and Whol, 2003; Manga and Kirchner, 2000) and sediment dynamics (Keller and Swanson, 1979; Gomi et al., 2001) to forcing steps and pools (Carlson et al., 1990; Montgomery et al., 1995; Buffington et al., 2002; Faustini and Jones, 1993) and is important for diversifying habitat types and increasing biodiversity (Ralph et al., 1994; Wondzell and Bisson, 2003). LWD dynamics and processes are known to vary widely along the length of a stream and through time (Keller and Swanson, 1979), and natural and anthropogenic disturbances can further influence in-stream wood and its interaction with the aquatic environment. The dynamics of LWD in headwater streams in particular are only recently beginning to receive research interest, having been overlooked in the past in favour of a research emphasis on higher order, lower gradient streams (Hassan et al., 2005). In addition, to date little research has been conducted on the impacts of natural forest disturbance on LWD dynamics.

A wood budget is a valuable framework for quantifying wood dynamics over a range of fluvial systems. It considers the flux of wood in a stream as a mass balance with definable inputs, outputs, and storage rates (Benda et al., 2003), which are known to vary predictably within a watershed according to stream size and dynamics (Keller and Swanson, 1979). Although the concept of the wood budget framework has been established for almost a decade, and has been in practical use for several decades longer, we are not aware of complete wood budgets that have measured all of the components in detail. Of the many papers that report partial wood budgets of different systems (e.g., Martin et al., 2001; Benda et al., 2002; Benda et al., 2004; Warren and Kraft, 2008), most are based on one-time in-channel wood inventories, with most of the components either estimated or considered to be negligible. To better understand wood dynamics in channels there is a need for accurate quantification of the wood budget through repeated annual surveys and detailed measurement of the individual components.

One promising but currently under-utilized application of a wood budget framework is the quantification of the impacts of riparian disturbances on wood dynamics. Forest disturbance can affect one or more components of the wood budget, and the impacts likely vary according to spatial location of the disturbed stream reach, as well as the time since the onset of the forest disturbance. In the interior of British Columbia (BC), wildfire and Mountain Pine Beetle (MPB) infestation are prevalent forest disturbances affecting enormous swaths of forest with important ecological and economic implications. From an aquatic ecosystem perspective, understanding and quantifying the impacts of these riparian disturbances is essential for mitigating and managing their impact. However, the wood budget of BC interior headwater streams has not been quantified, nor has the response of the wood budget components to these disturbances. Simulations and limited field studies on post-fire LWD dynamics suggest that streams will experience an increase in the volume and size of recruited wood following a fire (Young, 1994; Bragg, 2000; Chen et al., 2005; Jones and Daniel, 2008; Scherer et al., 2008). However, all of these studies are based on one-time measurements of LWD characteristics that do not provide comprehensive wood budgets. There are, to the knowledge of the author, no studies on relationships between MPB and in-channel wood.

The research presented in this paper addresses the research gaps identified above by building a detailed wood budget of headwater streams in the southern interior of BC through explicit measurements of the wood budget components of the study streams, and by using the wood budget as a framework for investigating impacts of fire and MPB on in-stream wood dynamics in the study streams. LWD dynamics are investigated in a disturbance context through the use of a wood budget framework, as developed and presented in detail by Benda et al. (2003). By working within a wood budget framework, it is possible to isolate where and how post-disturbances changes to LWD patterns are occurring. In this study, wood budgets are built for 12 Okanagan Basin headwater streams of different riparian disturbance regimes (fire, MPB and reference streams), based on repeated annual surveys. Sources of wood recruitment are identified, detailed budgets are developed, and an attempt made to identify disturbance induced changes in a range of LWD characteristics including absolute volumes of wood for each component of the budget as well as differences in wood stability and wood sources.

A lack of standardized metrics of LWD and stream size is a pervasive problem in LWD research. Hassan et al. (2005) suggest a matrix of wood to channel dimensions to determine relative wood and stream size. This matrix eliminates the issue of picking arbitrary minimum dimensions that do not reflect channel characteristics. To the knowledge of the author this matrix has never been employed, nor have the thresholds of relative wood size suggested by Hassan et al. (2005) been tested as predictors of wood characteristics. In this study, we utilize our wood budget data to test the usefulness of the relative wood sizes presented by Hassan et al. (2005) as predictors of wood mobility.

2.1.1 Site selection and description

The study area is located in the southern interior of British Columbia in the Okanagan Basin. Located on the Thompson Plateau, the Okanagan Basin lies in the rain shadow of the Cascade and Monashee Mountains. As a result, the Okanagan has a semi-arid climate with mean annual precipitation ranging from 250mm in the valleys to over 1000mm in the alpine and subalpine areas and with a mean annual temperature between 1.7 and 4.7ºC (Cohen and Kulkarni, 2001). Annual streamflow follows a snow-melt dominated hydrologic regime, with freshet occurring between April and July (Pinsent and Stockner, 1974). The basin has an average elevation of approximately 1120m, and is characterized by a high plateau between 1000 and 1800 m (Scherer and Pike, 2003). Its surficial geology is dominated by post-glacial deposits, with unconsolidated glacial till with numerous bedrock outcrops and thin morainal veneers (Roed, 1995). There are a number of biogeoclimatic zones in the basin, ranging from a Bunchgrass zone in the hot, dry valley bottoms to Montane Spruce and Engelmann Spruce-Subalpine Fir at higher elevations, where temperatures are generally cooler and the climate becomes wetter (Scherer and Pike, 2003).

The study streams consist of three fire sites and three corresponding reference control sites (henceforth referred to as “Ref -no burn”) located in the Interior Douglas Fir (IDF) zone, three Mountain Pine Beetle (MPB) sites and three corresponding reference control sites (henceforth referred to as “Ref - no MPB”) located in the Montane Spruce (MS) zone. Their geographic locations are shown in Figure 2.1. The burned stream sites were established in 2004, a year after a major wildfire swept through Okanagan Mountain Park. The MPB sites were established in 2005 in the MS zone due to a recent (less than 10 year old) beetle infestation in the area. The reference (undisturbed) streams were selected to ensure that there had been no major riparian disturbances within the last 80 years. However, none of the reference watersheds are free of logging activity, to varying degrees and intensity; cutblocks and logging roads are prominent features. However, buffer zones have been left around all of the upstream reaches. Logging of pine beetle infested forests around the MPB sites is extensive in an effort to salvage beetle killed trees. As a result, the riparian forest at each of the MPB sites is bordered by cutblocks on one or both sides of the riparian buffer zone.

Sites were selected according to their accessibility during the survey period, the forest cover type and biogeoclimatic zone, and their morphological and geographic characteristics. Streams were required to have widths less than 5 meters in the MS zone and less than 10 meters in the IDF zone. Stream gradient was required to be less than 15% (but was in fact less than 7.5% for all streams), and all sites had ‘U’ or shallow ‘V’ shaped valleys. Stream characteristics are provided in Table 2.1.

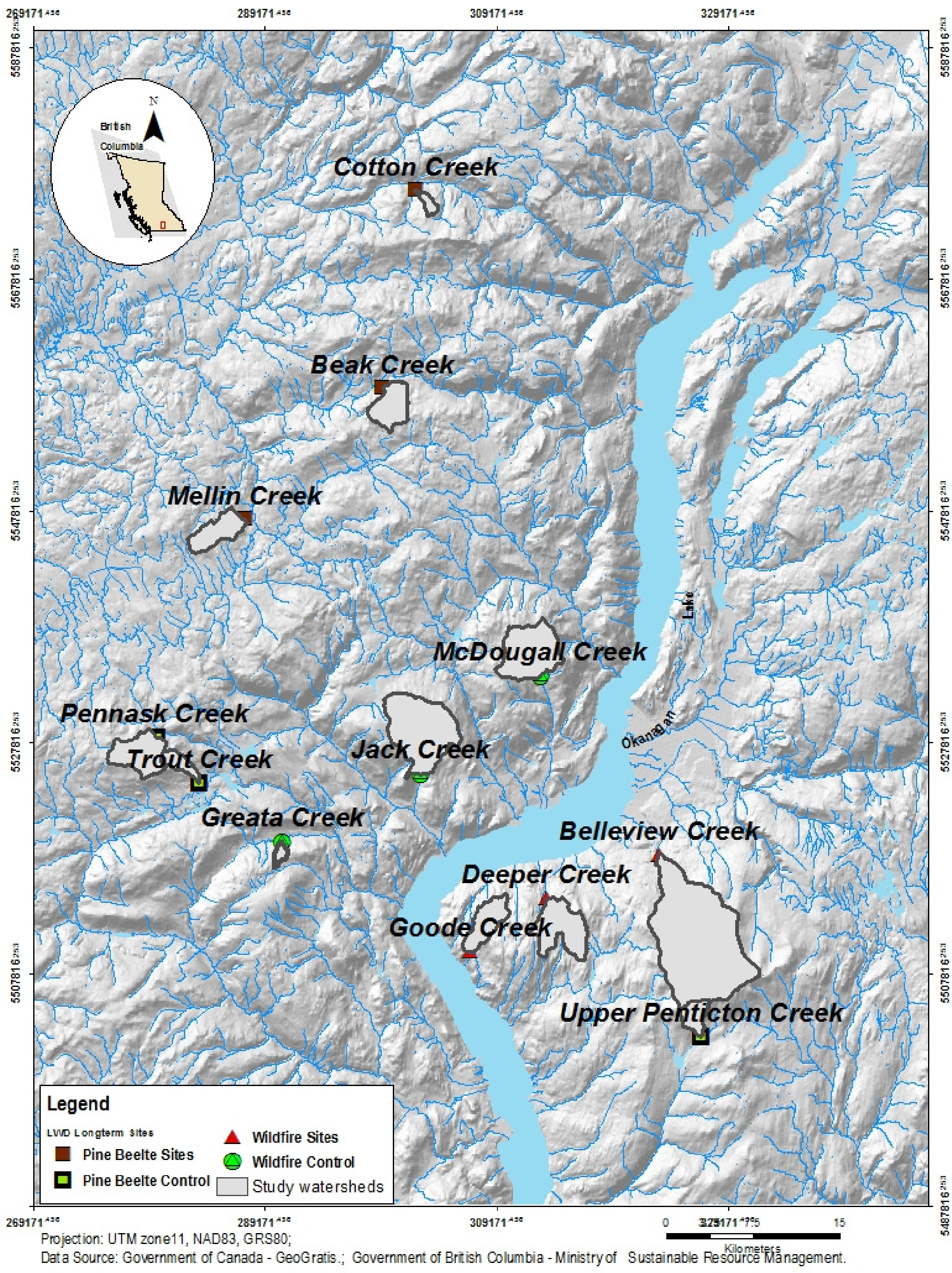

Figure 2.1: Geographic locations of the study sites in the Okanagan Basin, British Columbia

Table 2.1: Study reach characteristics (Note that all stream reaches are 100m in length, weighted D_{50} is calculated from the proportion of the bed covered by each sediment size, based on the Wentworth size classification)

Biogeo zone	Riparian condition	Stream	Basin area (km^2)	Average width (m)	Gradient (%)	D_{50} (mm)	volume of LWD (m^3)
Interior Douglas Fir	Fire	Bellevue	71.85	7.55	4.19	90	3.47
		Deeper	16.24	4.27	5.13	64	6.83
		Goode	9.63	2.68	3.37	64	6.10
	Ref – no burn	Jack	30.40	4.23	6.85	128	1.07
		McDougall	20.47	3.60	5.45	64	10.92
		Greata	1.51	3.22	3.20	23	0.86
Montane Spruce	MPB	Beak	9.87	2.13	6.46	128	0.89
		Mellin	9.56	1.61	3.06	90	2.44
		Cotton	1.85	2.26	8.11	32	2.99
	Ref – no MPB	Upper P	5.06	2.99	4.28	90	3.85
		Trout	3.97	2.12	2.93	16	1.74
		Pennask	13.03	3.94	2.74	64	4.88

2.1.2 Wood budget

The wood budget formulation used in this study is similar to the framework outlined in Benda et al. (2003). The wood budget of a stream reach can be written as

$$\Delta S = [I\Delta x - O\Delta x + \varepsilon]\Delta t \qquad (1)$$

where ΔS is the change in storage of LWD in the channel over the course of the study period, I is the annual volume of recruited wood and O is export and ε is an error term due to measurement errors. All terms are in units of wood volume (m^3), and are measured over the length of the stream reach Δx (100m in this study), over a specified time period Δt (reported annually for this study). The input component, I, can be broken down as

$$I = I_{h} + I_b + I_e + I_{ls} + I_f \quad (2)$$

where the term I_h refers to inputs from riparian forest sources, including mortality and windthrow, I_b includes inputs from bank erosion, I_e includes recruitment through exhumation from the channel bed and banks, I_{ls} includes landslide inputs and I_f includes wood transported into the reach through fluvial processes, i.e. recruited from upstream. The output portion of Equation 1 is broken down as

$$O = O_f + O_d \quad (3)$$

where O_f is fluvial transport of wood out of the reach, and O_d is volumetric loss to mechanical and biological decomposition and decay. In this study, each of these components is measured directly through repeated annual LWD surveys, and thus assumptions for the calculation of these components (e.g., Martin and Benda, 2001) are not required.

2.2 Methods

In field measurements of wood in the study streams, we employed the most commonly used definition of 10cm in diameter and 1m in length as the lower limit of wood measured.

In the initial survey year (2004 for the IDF sites and 2005 for the MS sites), LWD at each stream reach was tagged using a uniquely numbered metal tag secured to the log with wire. The LWD diameters were measured at large and small ends using callipers (as per Chen et al., 2005), the decay state was determined (as per Chen et al., 2008) (Table 2.2), and the coordinate of the ends of each in-stream piece were surveyed using a total station. Wood length was derived from the total station coordinates of the piece ends, and volume was calculated using the formula for a tapered cylinder, as per Chen et al. (2005). In each survey year subsequent to site establishment, new pieces of wood were tagged with coloured tags to identify their year of recruitment and to distinguish them from already present wood.

Each year, manual surveys of size and decay were conducted on new pieces, and the coordinates of the in-stream ends of every (new and pre-existing) log was surveyed using the total station. Manual surveys of diameter were only repeated again for all (pre-existing) logs in 2009. No survey was conducted in 2007, and wood volumes measured in 2008 encompassed wood recruited or lost over two years.

Table 2.2: Definitions of decay and submergence used in the LWD surveys at the study sites

Characteristic	Classification
Decay	1. The debris has intact bark, or at least >50% remaining, wood is hard with original colour, branches and twigs are present 2. The debris has trace of bark (<50% remaining), no twigs observed, wood has some surface abrasion 3. The debris has dark color, no bark or twigs, wood soft throughout with holes and openings
Submergence	1. Lower half of bankfull height 2. Upper half of bankfull height 3. Spanning the channel cross section 4. Partially buried 5. Any combination of the above positions

Wood recruitment sources were identified as follows: riparian sources (wood contributed directly from the adjacent riparian forest), fluvial sources (wood imported fluvially from upstream reaches), exhumation (wood exhumed from either the bed or banks of the stream), bank erosion (wood associated with areas of obvious bank failure) and mass wasting (wood associated with areas of obvious slope instability). Sources of recruitment were determined qualitatively through examining the stability, submergence and orientation of wood in the stream, as well as identifying evidence of bank or slope erosion, in a manner similar to Martin and Benda (2001).

For example, wood anchored on the bank or spanning the channel was assumed to be recruited directly from the riparian forest (i.e. riparian sources), whereas new wood oriented parallel to flow and loose in the channel was assumed to be imported from upstream through fluvial processes. For this study, different riparian processes of input such as wind and mortality, and toppled burned wood were not distinguished and were equally lumped into 'riparian sources'. Exhumed wood was in all cases still partially buried and could therefore be easily distinguished. To verify the importance of bank erosion as a source of wood recruitment, thalwegs and cross sections measured in 2005 were compared to channel surveys conducted in 2009 to identify actively migrating channels. Any evidence of lateral channel migration and bank failure was also recorded in the field. Air photo analysis of the study sites was used to look for evidence of mass wasting or landslides in the study watersheds.

Wood export was calculated as the volume of wood removed from the reach between subsequent surveys. Volumetric decomposition was calculated from wood that remained in the reach over the course of the survey, as its volume in the initial survey year minus its volume in the final survey year, scaled by the elapsed length of time. Gravitational decomposition and density changes of wood were not considered in this study and are assumed to be minor over such a short time period, although they are known to be important over the longer term (e.g., Chen et al., 2005). Burial was not included as an output in this study due to lack of field evidence, the generally coarse substrate, and the logistical impossibility of observing burial.

Channel dimensions and gradient were determined through thalweg and cross sectional surveys measured using the total station. Because only one of the study streams was gauged, annual discharge measurements were not available for 11 of the 12 streams. Relative wood size as defined by Hassan et al. (2005) was used to evaluate the impacts of different riparian conditions on recruit size and the impacts of wood size on wood mobility. Thresholds of wood size are based on the ratio of wood length to channel width and wood diameter to channel depth, and are set at 0.3 and 1, as per. Hassan et al. (2005) and shown in Table 2.3. These thresholds were defined by Hassan et al. (2005) as arbitrary divisions between wood sizes, and have not yet been applied or tested with real data. The half life (t_{50}) of wood in the streams as a function of decomposition and was calculated assuming an exponential decay function, as per Chen et al. (2005).

Table 2.3: The matrix of relative wood size defined by Hassan et al. (2005) (Note that L_l/W_b refers to the ratio of wood length to average channel bankfull width, and D_l/D_b refers to the ratio of wood diameter to average channel bankfull depth; wood is classified to one of these categories based on its combination of these ratios)

		L_l/W_b		
		<0.3	**0.3-1**	**>1**
D_l/D_b	**<0.3**	Small	Intermediate	Large
	0.3-1	Intermediate	Large	Large
	>1	Large	Large	Very Large

The analysis presented in this chapter aims to identify differences between disturbance regimes in LWD characteristics and budget. Differences in LWD characteristics between riparian conditions are determined by one way analysis of variance (ANOVA) or, when necessary, non-parametric Kruskal-Wallis test. When LWD characteristics were compared to external controls, variables were transformed to normalize their distribution as required for linear regression.

2.2.1 Uncertainties and sources of error

Measurement error in the field is likely to be low, as a total station was used for all surveys and is a highly precise instrument. There is likely to be error in the determination of wood sources, particularly distinguishing between fluvial and riparian recruits. Wood recruited from riparian sources before annual surveys were conducted could have been redistributed by the stream, particularly if recruitment took place during or before freshet. It would then have been mistakenly classified as a fluvial recruit. This error is likely larger for the 2008 measurement as no survey was conducted in 2007. At larger streams with large fluvial transport rates, there could be expected to be significant underestimation of riparian recruitment in 2008.

Truncating the size of wood measured at 10cm diameter and 1m length underestimates the volume of relatively sized small wood (as per the matrix of relative wood sizes), particularly in smaller streams. Thus, it should not be assumed based on data presented in this chapter that there was a deficiency of small and intermediate sized wood in the study streams.

2.3 Results

We first report detailed results on wood recruitment volume and characteristics for the study reaches. Then we report results on wood output through decay and fluvial transport from the reaches, and the relationship between relative wood size and wood mobility. Finally, we discuss wood storage and characteristics. Through the reporting we consider how the disturbance regime influences the LWD budgets and characteristics.

2.3.1 Wood recruitment

Details of the annual wood budget are presented in Table 2.4. Total annual wood recruitment (the sum of the 'input' component in Table 2.4) ranged from 0.06m^3/100m/yr at Beak Creek, a MPB site in the MS biogeoclimatic zone to 1.02m^3/100m/yr at Bellevue Creek, a burned site in the IDF biogeoclimatic zone. Sources of input were variable between streams, but were primarily dominated by riparian sources (including mortality and windthrow), ranging from as little as 0.02m^3/100m/yr at Jack to 0.77m^3/100m/yr at Goode Creek), and fluvial inputs ranging from $0.00m^3$/100m/yr at Trout Creek to $0.27m^3$/100m/yr at Bellevue Creek. Fluvial recruitment was less than $0.05m^3$/yr in all cases except Bellevue Creek ($0.27m^3$/100m/yr), Deeper Creek ($0.17m^3$/100m/yr) and McDougall Creek ($0.16m^3$/100m/yr), and was a smaller quantity than riparian recruitment in all cases but at Jack and McDougall Creeks. In most other cases, riparian recruitment was between two and five times more important than fluvial recruitment, and was as much as 55 and 73 times as important at Cotton and Trout Creeks, respectively. Exhumation from the bed and banks was important in some streams. Comparison of digitized thalweg lines from 2005 and 2009 revealed lateral channel migration was negligible in all cases but one; the thalweg at Bellevue moved laterally at a rate of 0.3m/yr on one meander bend, and 10.51% of wood recruited to the reach came from bank erosion. There was no evidence of landslides within the 100m study reaches or immediately upstream, in part because site selection excluded sites with steep, tightly confining valley walls prone to mass wasting.

Table 2.4: Summary information on wood budget components for the study reaches (units: volume of LWD per 100m reach per year (m^3/100m/year))

		Input						**output**		
Disturbance	stream	Riparian	Bank erosion	exhumed	other	unknown	fluvial	fluvial	decay	storage
Fire	Bellevue	0.65	0.10	-	-	-	0.27	0.51	0.00	0.51
	Deeper	0.48	-	-	-	0.01	0.17	0.27	0.05	0.34
	Goode	0.77	-	-	-	0.07	0.03	0.16	0.07	0.64
Ref - no fire	Jack	0.02	-	0.02	-	-	0.04	0.16	0.06	-0.14
	McDougall	0.04	-	0.03	-	0.00	0.16	0.33	0.26	-0.36
	Greata	0.07	-	0.00	-	0.01	0.02	0.12	0.03	-0.05
MPB	Beak	0.05	-	-	-	-	0.01	0.07	0.02	-0.02
	Mellin	0.22	-	-	-	0.01	0.02	0.02	0.03	0.19
	Cotton	0.49	-	-	-	0.01	0.01	0.03	0.03	0.45
Ref - no MPB	Upper P	0.09	-	0.01	-	-	0.05	0.17	0.06	-0.09
	Trout	0.13	-	0.00	-	-	0.00	0.15	0.02	-0.04
	Pennask	0.09	-	0.05	0.00	-	0.02	0.09	0.05	0.02

The contribution of exhumation to wood input was as high as 30% at Pennask Creek (from 2 pieces of wood) and 25% at Jack Creek (from 1 piece of wood). At Upper Penticton Creek and McDougall Creek, exhumation accounted for 6.69% and 12.5% of wood input, respectively. Whereas exhumation was an important input process at most of the reference streams, there was no exhumation at the burned or MPB sites. Otherwise, there did not appear to be any ubiquitous environmental controls on the exhumation of wood from channel beds and banks that explain the presence, absence or magnitude of exhumation at the sites. Exhumation was not strongly related to stream size, gradient or substrate.

Wood recruited from riparian processes was strongly influenced by riparian condition (Figure 2.2A). There was more than an order of magnitude more wood recruited through riparian processes at burned sites relative to their controls (averages of $0.63m^3/100m/yr$ and $0.04m^3/100m/yr$ respectively), and the difference was significant (p <0.01). An average of 2.5 times more wood was recruited at MPB sites than at their controls ($0.25m^3/100m/yr$ and $0.10m^3/100m/yr$ respectively), although the difference was not significant. Recruitment rates were slightly but not significantly higher at the MS reference sites relative to the IDF reference sites. In addition, there was much less variation in annual recruitment rate between streams at the reference sites relative to the disturbed sites. Variability was highest at the MPB sites. There were no significant differences between riparian conditions in the volume of wood recruited by fluvial sources (Figure 2.2B).

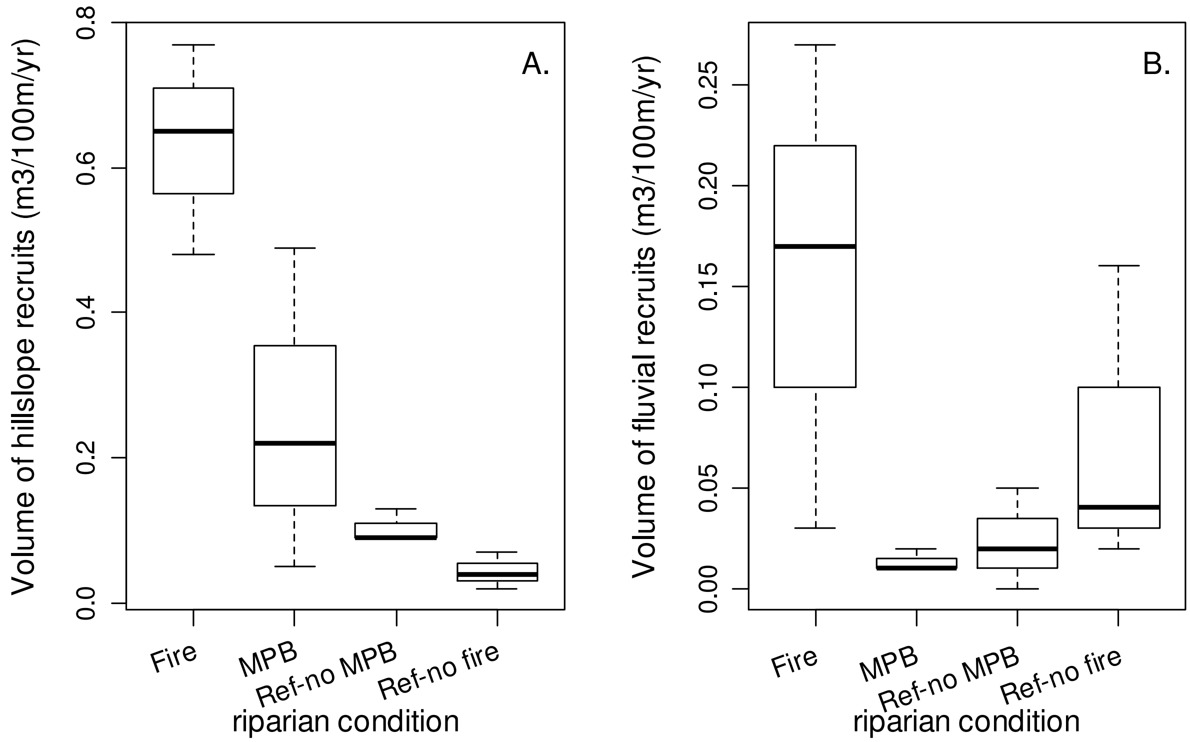

Figure 2.2: Volume of wood recruited: A) directly from the adjacent riparian forest through mortality or blowdown as a function of riparian condition; and B) through fluvial transport from upstream of the study reaches as a function of riparian condition

Figure 2.3 shows the inter-annual variation in LWD input in the study streams. There was significantly more wood recruited at the burned sites in 2006, 2008 and 2009 relative to the reference streams ($p < 0.05$). The burned streams showed high variation in wood recruitment between streams relative to the reference streams, particularly in 2005 and 2009. There were no years in which there was significantly different recruitment at the MPB sites relative to their references. There was, however, high variability at the MPB sites in 2009, due to a high volume of deadfall at Cotton Creek. Both sets of reference streams displayed relatively low variability, particularly the Ref – no burn streams.

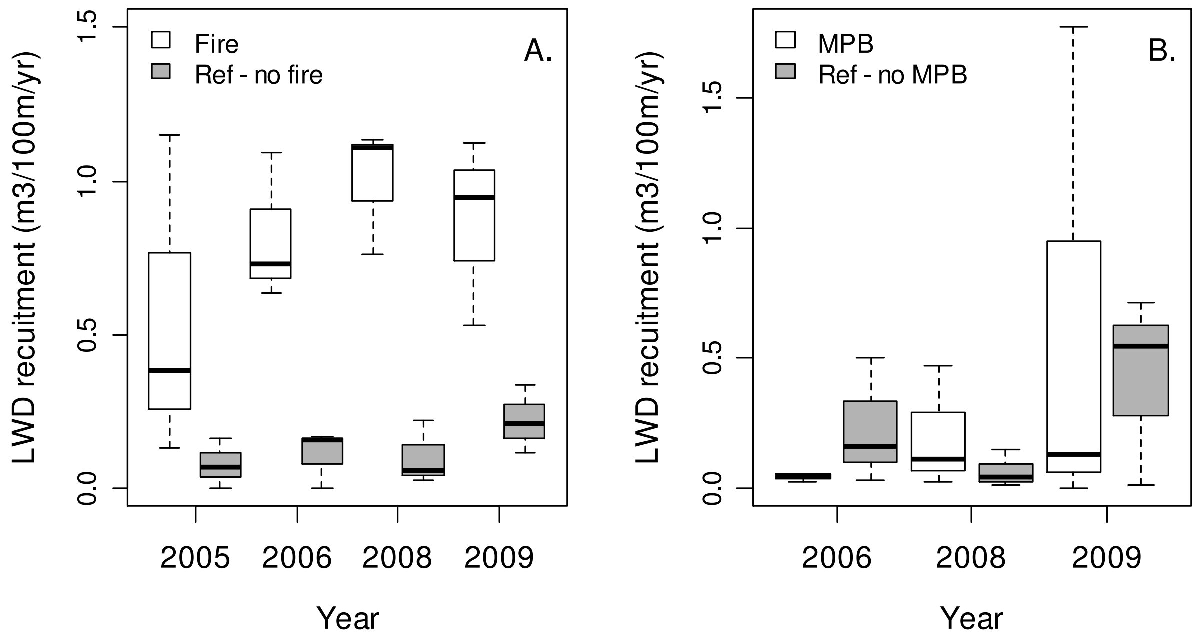

Figure 2.3: Inter-annual variability in LWD recruitment in the: A) burned and Ref – no burn study streams, and B) MPB and Ref – no MPB streams, in units of m^3/100m/yr (Note that the 2008 value is half of the value of recruited wood between 2006 and 2008, as measurements were not conducted in 2007)

2.3.2 Recruited wood size

In addition to changing the volume of recruited wood, riparian disturbance changed the size of recruited wood (Figure 2.4). In the reference streams, the largest proportion of wood was recruited in the Large relative wood size range (Figure 2.4 B and D), with only a small proportion of recruits in the largest (Very Large) category. There was significantly ($p < 0.05$) less wood recruited in the largest (Very Large) size category than in the Large size category in both the Ref – no fire and Ref – no MPB streams. However, at the disturbed streams, as much or more wood was recruited in the largest (Very Large) size category as in the Large size category, and there was a general increasing trend in the proportion of recruits with increasing size category (Figure 2.4 A and C). Overall, at the disturbed streams there was a shift towards larger relative recruit sizes and an important component of recruits that were larger than the channel dimensions, both in width and depth.

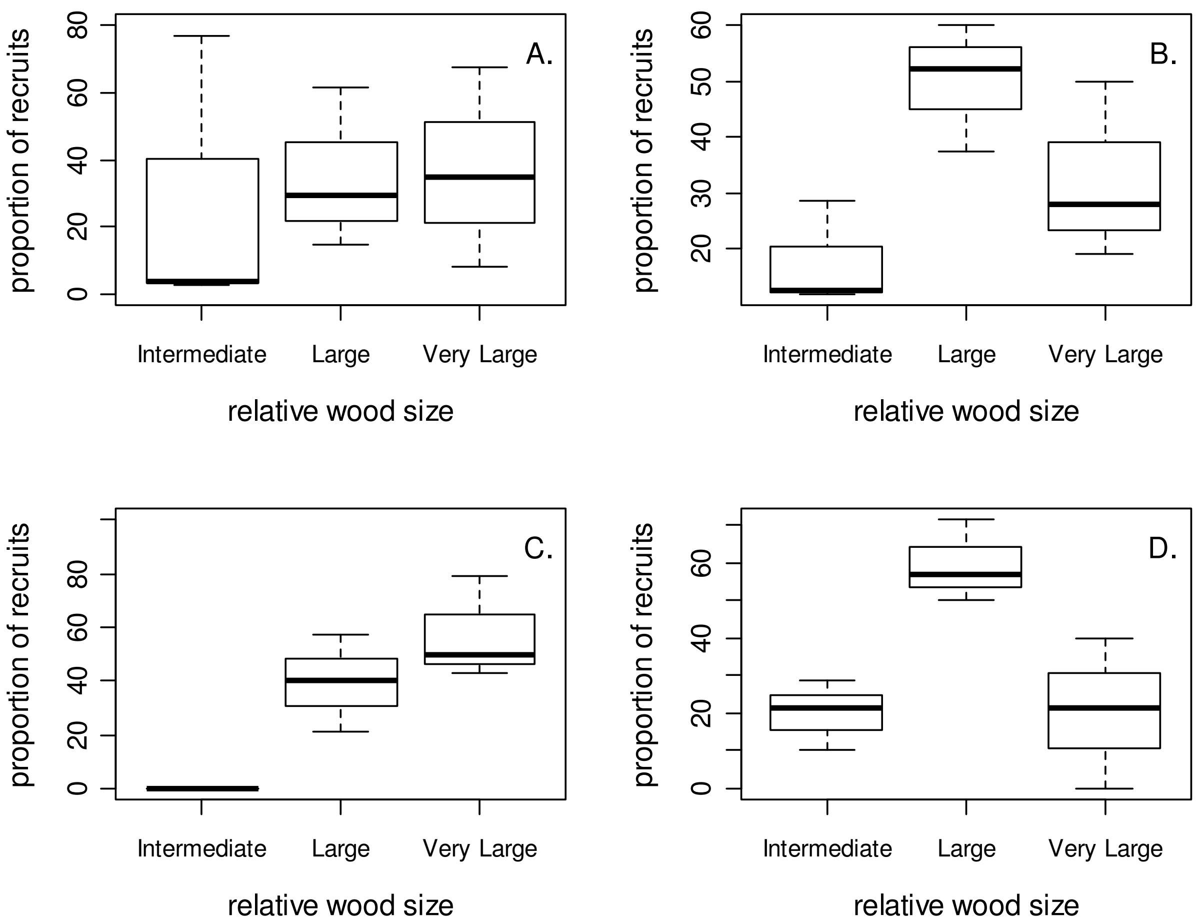

Figure 2.4: The proportion of recruits in three relative LWD size categories at the: A) burned, B) Ref – no burn, C) MPB, and D) Ref – no MPB streams (Note that proportions are calculated here in terms of number of pieces rather than volume)

2.3.3 Wood output through fluvial export and decomposition

Total average annual output in the study streams ranged from as little as $0.02m^3/100m/yr$ at Mellin Creek to as much as $0.51m^3/100m/yr$ at Bellevue Creek, and was an average of $0.21m^3/100m/yr$ across all the streams (Table 2.4). Output in these study reaches was either through decomposition or fluvial export; the relative contribution of each component was variable between streams (Figure 2.5). In general, fluvial export was the most important component of output in the study streams, and in the case of Bellevue Creek with high fluvial wood turnover, made up the entire output term. In the other streams, fluvial export was an average of five times greater than decomposition, with the exception of Cotton and Mellin Creeks where decomposition was slightly larger than export.

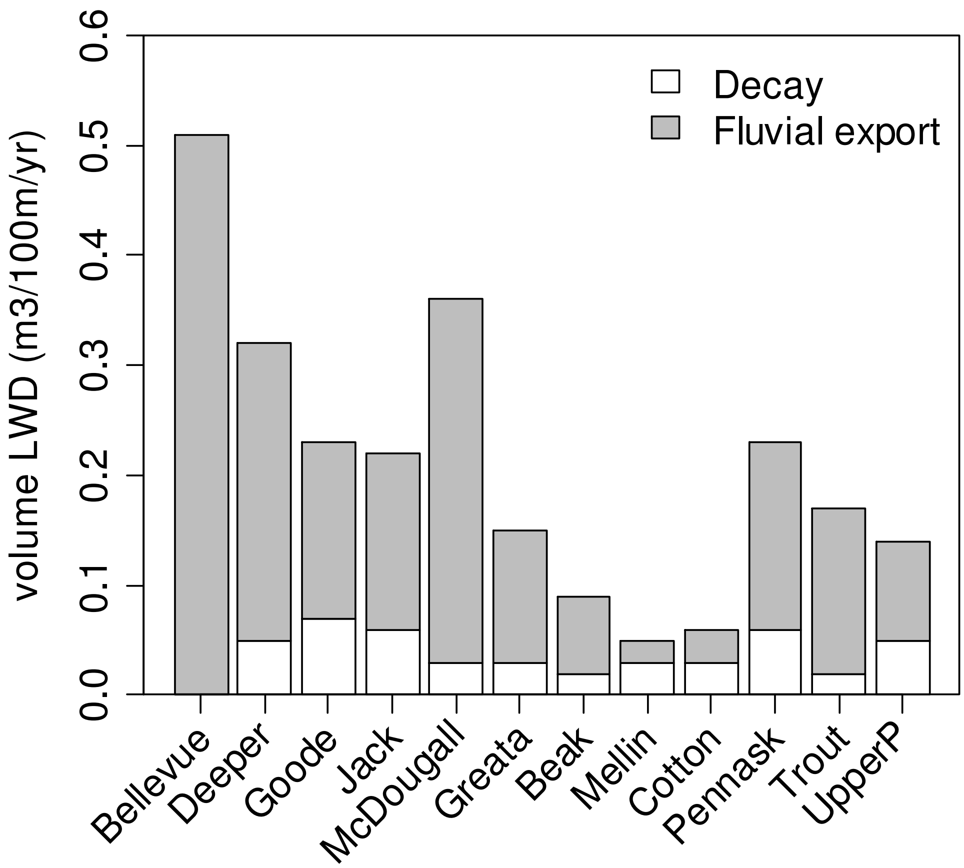

Figure 2.5: Average annual output of LWD in the study reaches, stratified by the relative contribution of decay and fluvial export (Note that Average annual fluvial export is an average of annual export for each study year, and average annual decay is calculated as the average rate of decay over the entire study period)

There was measurable fluvial wood export in all streams, regardless of size. However, fluvial export and wood mobility in the channels was strongly controlled by its length relative to the channel width. Over the 5 year period of the study, the average length of the five longest pieces of exported wood from each channel reach showed a maximum length/channel width (L_l/W_b) ratio below 1:1 (Figure 2.6A). Of the 11 streams plotted in Figure 2.6a (Bellevue is not shown because it had no stable wood), L_l/W_b ranged from 0.5 (at Pennask Creek) to 0.97 (at Beak

Creek), with an average ratio of 0.75. This compares to average maximum L_l/W_b of 1.66 for stable pieces.

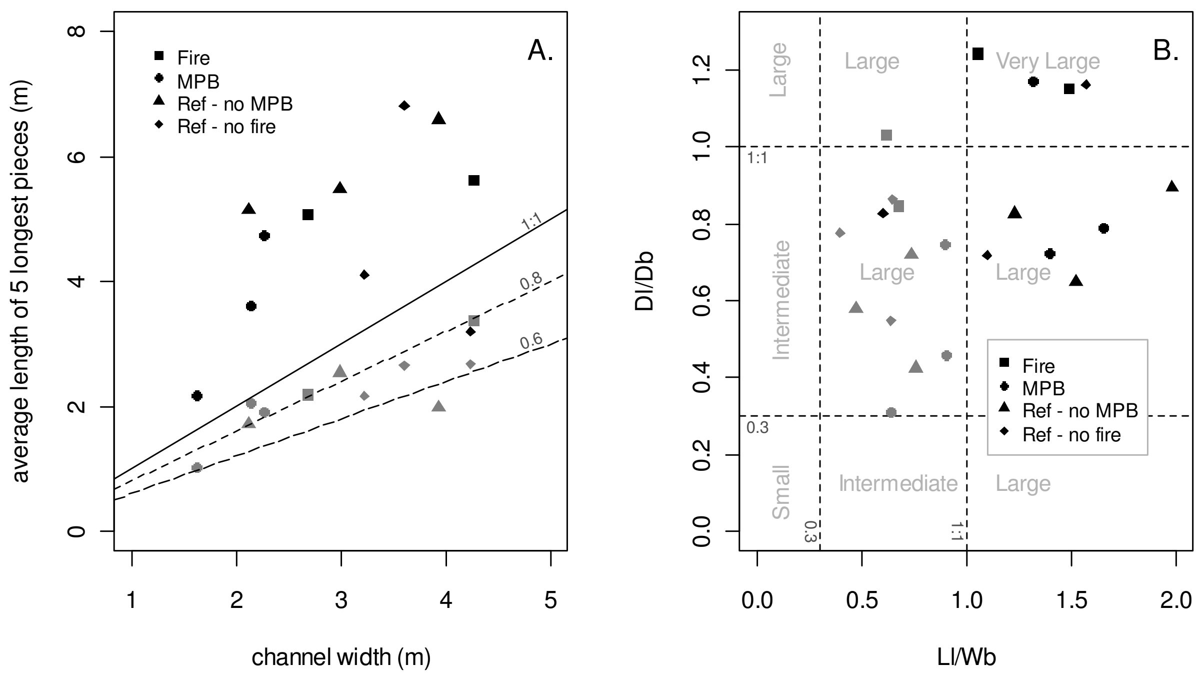

Figure 2.6: A) Average length of the 5 longest pieces of mobile (exported) and stable wood in each of the streams plotted against average bankfull channel width. B) Largest five pieces (by volume) plotted by their length to bankfull width ratios (L_l/W_b) and diameter to bankfull depth (D_l/D_b) ratios for the 11 study streams, relative to the 0.3 and 1 ratios of relative wood size defined by Hassan et al. (2005). (Note that: Bellevue Creek is not included in either of the plots since there were no stable pieces; grey points represent exported wood, and black points represent stable wood, and relative wood sizes are defined according to the L_l/W_b and D_l/D_b matrix outlined in Table 2.3.

Figure 2.6B further illustrates the importance of the relative size of LWD in determining mobility and wood export. Plotting the average dimension of the five largest (by volume) exported and stable pieces for each channel relative to the matrix of relative LWD size defined by Hassan et al. (2005), there was a distinct segregation of exported and stable pieces based on their relative size. The maximum threshold of exported wood was the Large relative size category, with all but one of the streams falling in this size category, despite significant variability within this size category. The relative size of mobile and stable wood is well compartmentalized by the matrix presented by Hassan et al. (2005). Wood that can be described in terms of relative size as Small, Intermediate, or Large can be either mobile or stable, whereas large wood above the 1:1 ratio (Very Large wood) can be assumed to be stable.

Figure 2.7 breaks down the proportional export of wood by relative size class. Small wood was not considered, as wood surveys were truncated at 1m in length and 10cm in diameter, and thus small relative wood sizes were not common in our sampling. As a result of their small channel widths and the minimum LWD length (1m), there were no pieces of intermediate sized wood measured at either Beak Creek or Cotton Creek, and only four such pieces at Mellin Creek, all of which were stable. Thus, the proportional export of intermediate sized wood at the MPB streams is null. With this exception, all of the riparian condition categories demonstrated a decrease in proportional export of wood with increasing relative size category. The proportional export of intermediate sized wood is approximately 2, 6 and 8 times higher than the proportional export of Very Large sized wood at the burned, Ref – no burn and Ref – no MPB streams, respectively. However, this difference between export of intermediate and Very Large sized wood is only significant at the Ref – no burn streams ($p < 0.05$). Export of Intermediate and Large sized wood is higher at the burned streams relative to the Ref – no burn, although the difference is not significant. The proportional export of wood from the Large size fraction is higher at the Ref – no MPB streams than at the MPB streams, although the difference is not significant. The proportional export of Very Large sized wood is approximately identical at all of the streams, regardless of riparian condition, although the values at the burned streams are heavily skewed by the high export rates at Bellevue Creek.

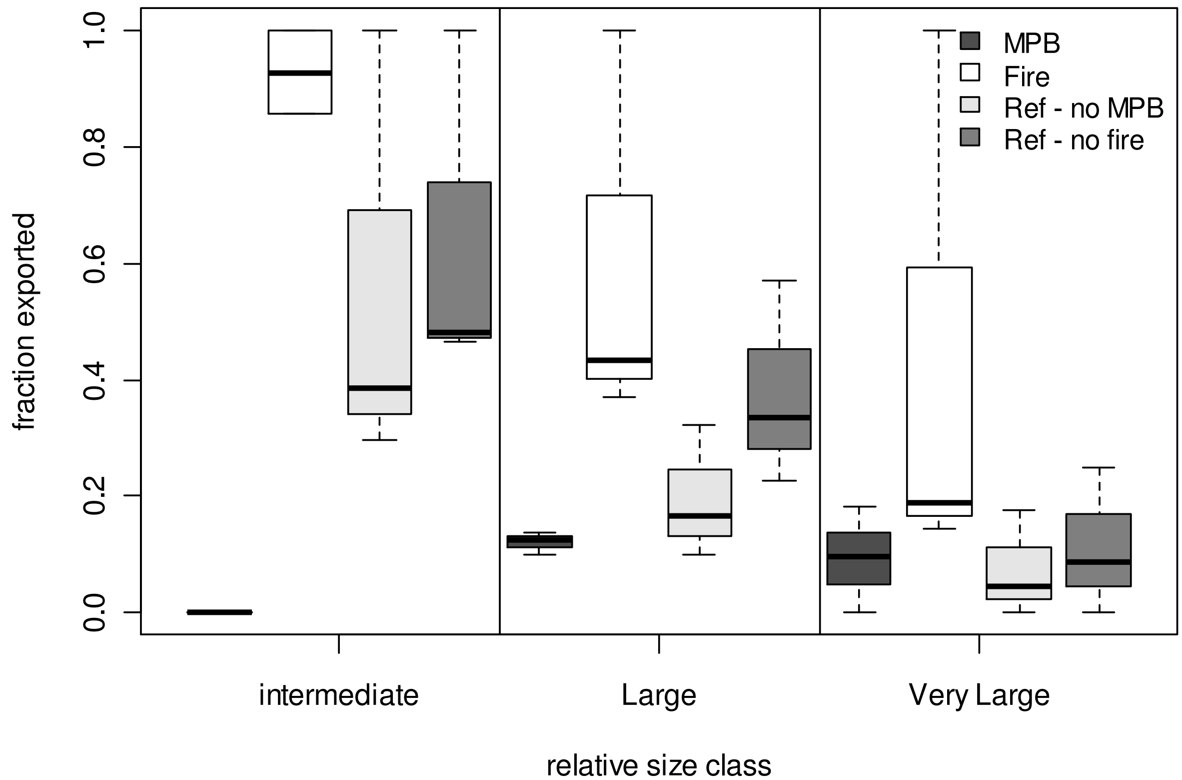

Figure 2.7: The proportional export of (2005) wood, classified by relative size class and stratified by riparian condition

There was a significant ($p < 0.001$, excluding the MPB streams) correlation between fluvial inputs and fluvial outputs, although the MPB streams do not fit well with the trend set by the other streams (Figure 2.8A). In all cases, more wood was exported from the reach than was fluvially imported, indicating a net negative fluvial flux in the reaches. On average, the fluvial export term was 3.6 times higher than the fluvial import term, with fluvial exports supplemented by the high volumes of riparian recruits in each of the reaches. The difference between the fluvial export and import term was the smallest at the burned streams (a ratio of 3:1), although there were no significant differences between riparian conditions. Additionally, there is a weak but significant positive relationship between the percentage of wood pieces in accumulations (wood jams) and the fluvial export of wood ($p < 0.05$, $R^2 = 0.45$) (Figure 2.8B).

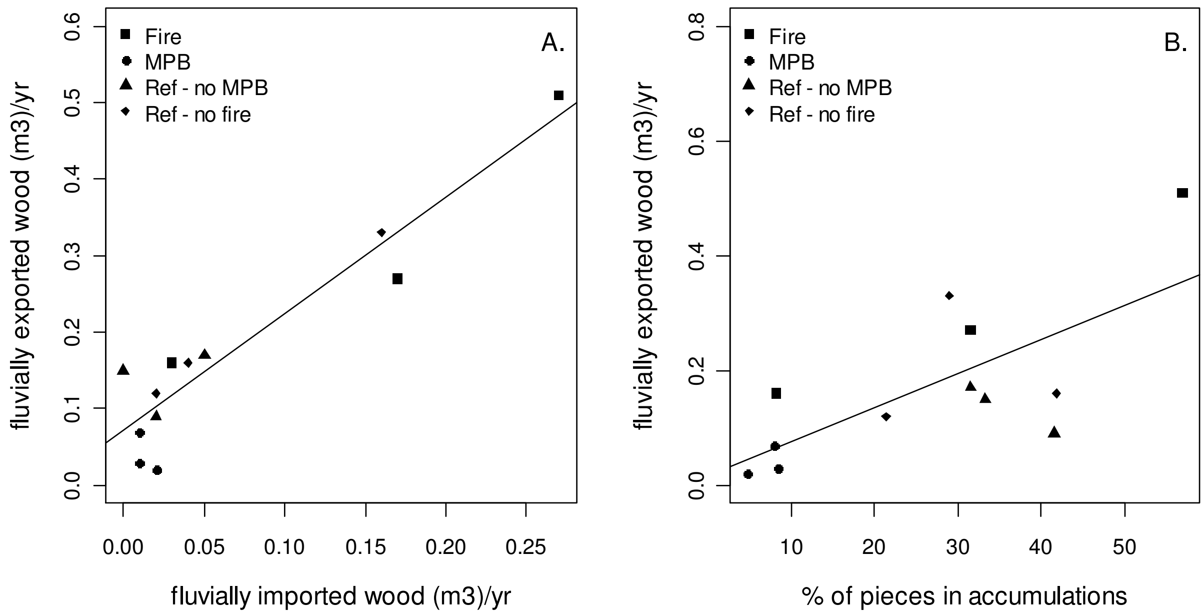

Figure 2.8: The relationship between fluvially exported wood: A) fluvially imported wood (*p* < 0.001, excluding MPB sites), and B) the percentage of pieces of wood in jams, defined as accumulations of two or more pieces of wood (*p* < 0.05, R^2 = 0.45)

Figure 2.9 shows the inter-annual variability in LWD export within disturbance types. Table 2.5 shows the annual peak discharges for Upper Penticton Creek, the only stream that was gauged. We use this data here under the assumption that it is representative of the relative high/low flow conditions at the other streams over the course of the study years, such that 2005 and 2007 were low flow years, and 2006 and 2008 had relatively higher flows, with 2009 falling somewhere in the middle. There was a high variability in wood export between riparian conditions and through time. The control sites in particular seemed to vary closely with the inter-annual variability of peak discharges at the Upper Penticton Creek gauging station (Table 2.5), with low values in 2005 followed by high export rates in 2006, lower values in 2008 (a result of the low discharge in 2007 being factored into the export calculation for 2008) and a slightly higher value for 2009 that was nonetheless lower than the high value in 2006. Export of wood at the disturbed streams followed similar but weaker patterns and relationships of wood export and discharge, but the relationships between export at disturbed sites and their controls were not consistent between years.

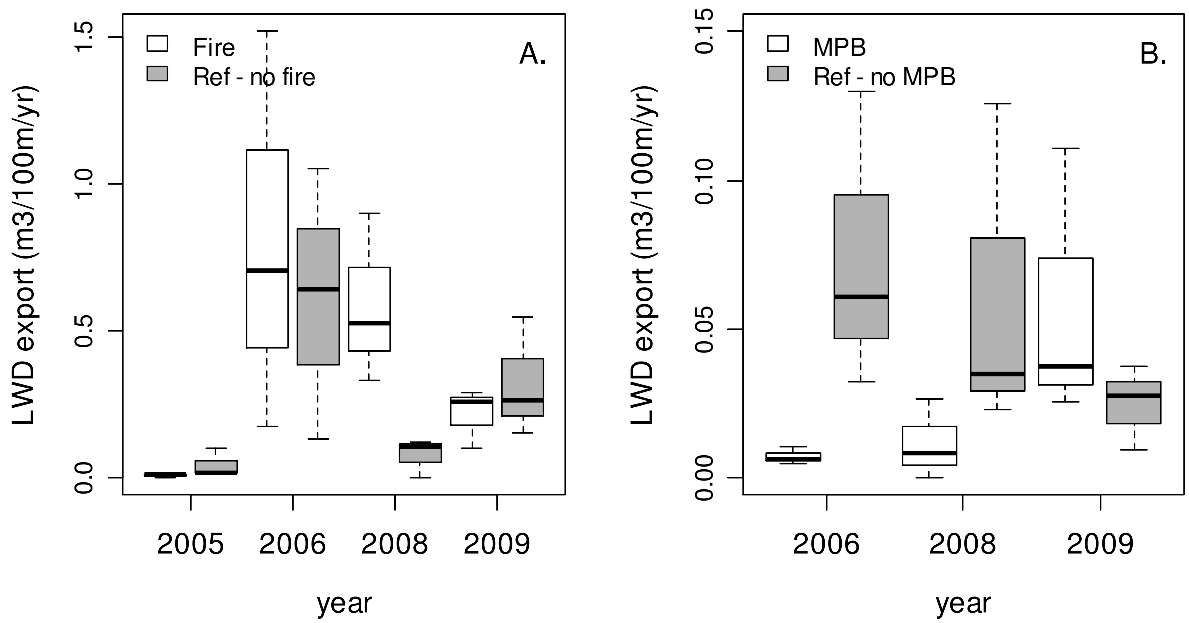

Figure 2.9: Inter-annual variability in LWD export (m^3/100m/yr): A) burned study streams and their references; and B) MPB study streams and their references

Table 2.5: Peak flows at Upper Penticton Creek 240 gauging station

Year	Peak Discharge (m^3/s)
2005	0.75
2006	1.71
2007	0.81
2008	1.79
2009	1.14

Absolute rate of decomposition was relatively constant between the study streams, ranging from 0.02m^3/100m/yr at Trout and Beak Creek to 0.07m^3/100m/yr at Goode Creek (Table 2.4), and with a very high decomposition rate of 0.26m^3/100m/yr at McDougall Creek. Decomposition was not measured at Bellevue – all of the wood from 2004 was fluvially transported from the reach by the final survey year, 2009. The absolute decomposition rate was largely determined by the total volume of wood in the stream. Thus, although the absolute decomposition rate varied from 0.02 to 0.26m^3/100m/yr at different streams, the percentage of total wood volume lost to decay was relatively constant between streams, ranging from 2 to 9% and averaging 4.3% at all streams but Jack Creek, which had a very high percentage of 24% (Table 2.6).

The half life (t_{50}) of wood in the streams as a product of decomposition ranged from as little as 24 years at Jack Creek to as much as 110 years at Pennask Creek, but was generally a consistent average of 71 years, with a 95% confidence internal of ±15 years (Table 2.6). This means that if the wood is not exported out of the reach in the next 71 years it will have lost, on average, half of its volume to decay. There were no apparent differences in decomposition rate between riparian disturbance regimes or between biogeoclimatic zones. Furthermore, there was no relation between t_{50} and decomposition state of LWD in the stream.

Table 2.6: LWD Decomposition rates at study sites (units: m^3/100m /yr, t_{50} refers to the number of years necessary to reduce the volume of wood in the channels by half assuming no additional inputs, based on the rates calculated between initial and final years of surveying

Disturbance	Stream	% annual biomass loss to decay	t_{50} decomposition (years)
Fire	Bellevue	n/a	n/a
	Deeper	3.0	-106
	Goode	3.1	-54
Ref – no fire	Jack	24.2	-24
	McDougall	8.4	-58
	Greata	9.2	-54
MPB	Beak	4.9	-74
	Mellin	1.9	-90
	Cotton	2.1	-75
Ref – no MPB	Upper P	4.3	-72
	Trout	2.1	-105
	Pennask	4.3	-110

2.3.4 Wood storage

There was a net positive change in storage at the two disturbed riparian treatments, fire and MPB (Figure 2.10). Average storage in the streams of the two reference treatments was negative, indicating depleting LWD storage. The depletion at the MS reference sites (Ref – no MPB) had a very slight negative storage value, with a small net depletion. The IDF reference streams (Ref – no burn) had the highest average depletion rates, with the highest depletion rates of $-0.36m^3$/yr at McDougall Creek (Figure 2.10). Positive storage was highest at the burned sites, and was significantly higher at burned sites relative to unburned sites ($p < 0.01$). Although MPB sites had positive storage and a larger magnitude of storage than their Ref – no MPB sites, the difference was not significant.

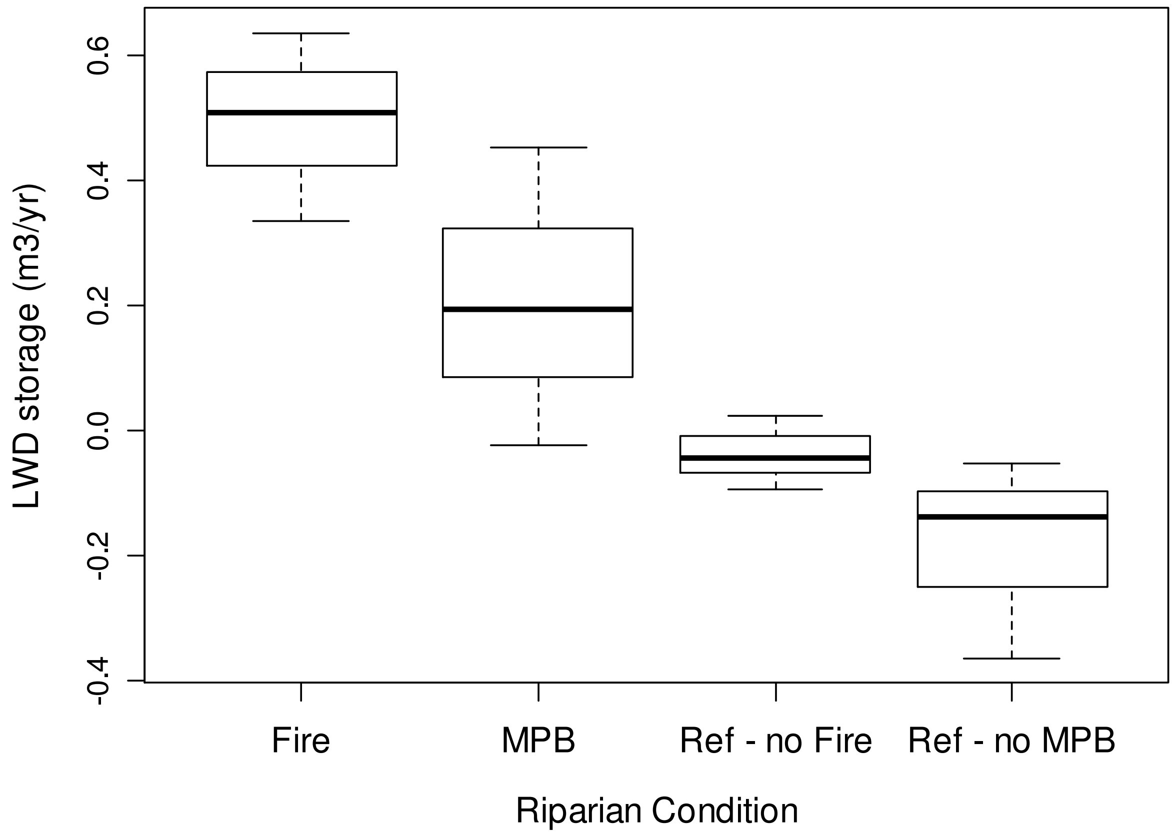

Figure 2.10: Changes in net storage for four riparian conditions

2.4 Discussion

This chapter provides detailed wood budgets of 12 headwater streams in the Okanagan Basin of the central interior of British Columbia. A wood budget is a useful framework for the study of spatial and temporal patterns of wood dynamics in streams. We believe that the patterns represent in-channel wood conditions in small streams in the Okanagan and similar landscapes. Although the study encompasses a relatively short period of time, it provides detailed information on annual patterns of wood recruitment, output and storage in small streams. In addition, the study provides insightful information on the impact of disturbance regimes on wood dynamics in streams. To our knowledge, this is one of the first attempts to develop a detailed wood budget based on quantification of the individual components, and the first attempt at using the wood budget to quantify the impacts of riparian disturbance on LWD dynamics. Of the study streams, three have had their riparian zones burned by the 2003 Okanagan Mountain Park fire, and a further three streams have had recent (<10 year) mountain pine beetle infestations in their riparian forests. Each of these sets of three streams has been paired up with three reference streams in their respective biogeoclimatic zones. By using a wood budget framework for analysis it is possible to identify how the specific components of the wood budget respond to external factors including riparian disturbance.

2.4.1 Input term

By conducting repeated measurements of instream wood over a number of years with explicit measurement of the different wood budget components, we have eliminated the need to estimate parameters based on theoretical and perhaps misleading predictions. For example, by using a theoretical estimation of bank erosion input in similarly sized/steep streams as ours, Benda and Associates (2004) found that bank erosion dominated input sources by, in many cases, an order of magnitude more than tree mortality inputs. By contrast, based on annual observations at our study sites, we found that wood recruitment to the study reaches is dominated primarily by riparian inputs (by mortality and windthrow), followed by fluvial imports and exhumation. Similar to the findings of May and Gresswell (2003), bank erosion in these headwater streams (which are generally small, steep and lack the energy to erode laterally, and in many cases alluvial banks) does not contribute to wood recruitment in all cases but Bellevue Creek, the largest of the streams and a burned stream. Recent research has suggested that riparian wildfire promotes channel widening and migration (Eaton et al. 2010). Field observations by the author suggest that the banks at Bellevue have been weakened by the 2003 fire and are less cohesive and more prone to erosion. This may have promoted lateral migration in Bellevue Creek; however this needs to be confirmed by a more targeted field study. Sections of Bellevue Creek that are confined by bedrock banks show no lateral migration throughout the study, and bank erosion is limited to alluvial banks. Air photo and field inspection revealed no evidence of landslides and mass wasting at the study sites. Furthermore, study sites were chosen to minimize the steepness of the surrounding valley walls, and as such the likelihood of mass wasting events is low.

Riparian inputs dominated recruitment and ranged from $0.02m^3/100m/yr$ at Jack Creek to $0.77m^3/100m/yr$ at Goode Creek, and showed strong stratification between riparian conditions. Burned sites had more than an order of magnitude more recruitment from riparian sources than their reference streams. MPB sites had 2.5 times as much wood than their reference sites. These results align with expectations. Wildfires produce an immediate surge in standing snags and corresponding deadfall. By contrast, there is a delay between initial infestation by mountain pine beetle and the death of the tree, and still further delays until the mortality translates into susceptibility to toppling or breakage. The volume of riparian recruitment at the MPB presently shows an initial trend towards an increase, and is expected to increase over the next several decades.

The occurrence of intensive salvage logging in forests surrounding the riparian buffer zones of the MPB study sites may also be having a significant impact on the wood budgets of the study streams. All of the MPB study sites are adjacent to one or more cutblocks, exposing them to high winds. Coupled with the increasing mortality of the stands, this increased exposure to wind may accelerate toppling rates relative to what would otherwise be predicted (Liquori, 2006). Indeed, Cotton Creek was observed to be particularly subjected to high wind, and has correspondingly high rates of recruitment (many of the recruits were observed to be from windthrow). Comparatively, Beak Creek is sheltered from wind by a dense buffer zone and has the lowest rates of riparian inputs of any of the MPB streams. To verify the possible impacts of riparian forest exposure to clear cuts and subsequent increased wind exposure, it would be necessary to modify the study by distinguishing between mortality and windthrow.

In previous studies, exhumation as a source of input has been ignored (Martin and Benda 2001; Benda and Sias 2003), or considered to be inconsequential (Benda et al. 2002). However, in our study streams we found that exhumation can provide as much as 30% of the wood inputs, even in small headwater streams. Although no external controls were found to influence exhumation, it is notable that while exhumation is an important source of LWD at most of the reference sites (either through exhumation from the bed or gradual exhumation from the banks) it is absent at the disturbed sites. The reasons for this are likely different for the burned and MPB sites. At the burned sites, the Okanagan Mountain Park fire effectively scorched the forest soil, burning through the soil layer, including the root systems of the tree and any organic matter buried in the floodplain and banks. Much of the buried material in the streams themselves would also have been burned. At the MPB sites, the lack of exhumation is likely due to the small stream sizes, high gradients, large bed substrates and lack of alluvial banks, limiting bed degradation and bank erosion.

In addition to influencing recruitment rate and source of wood, riparian disturbances were found to influence LWD recruit size. In the undisturbed streams, there was significantly less wood recruited in the Very Large size class than in the Large size class. However, in both riparian disturbances there was as much or more wood being recruited to the largest size category than the Large size class. This is likely related to the higher rates of riparian recruits in the disturbed streams, which are likely to be larger than wood transported into the reach by fluvial processes.

2.4.2 Output term

Fluvial imports into the reach were the second largest source of input in the study streams. In other studies, fluvial inputs are often considered in conjunction with or in relation to fluvial exports, and assumptions are made about their relative values that may not reflect reality. For example, in trying to parse out the proportion of wood recruitment due to fluvial and riparian inputs, Warren and Kraft (2008) consider a simulation in which fluvial imports and fluvial exports are the same. Martin and Benda (2001) and Benda et al. (2001) omitted the fluvial input and output term but considered change in storage to represent recruitment over time. Our findings suggest that fluvial import and export are strongly correlated, but are not 1:1. In our study streams, more wood is exported from the study reaches than fluvially imported. Fluvial export in the reach was also found to reflect temporal patterns of annual discharge variability. Another assumption made when estimating the fluvial export or transport component of the wood budget is the assumption that wood transport occurs from wood jam to wood jam, and thus jam spacing and characteristics can be used to estimate fluvial transport (Martin and Benda, 2001). If this were true, one would expect to see a strong relationship between the percentage of wood pieces in accumulations and the volume of exported (transported) wood. We observe only a weak such relationship in our reaches. We observe fluvial export in all of the study streams regardless of jam characteristics. Streams with highly stable wood and very little fluvial reorganization of wood in the channels transported wood, suggesting that the nature of jams in a reach is not an adequate predictor of wood mobility in headwater streams.

The matrix of relative wood size presented by Hassan et al. (2005) was applied and tested as a predictor of wood stability. Both the diameter and length of wood in relation to channel depth and length, respectively, were shown to strongly influence wood stability, and in both cases the ratio of 1:1 suggested by Hassan et al. (2005) was shown to be a definite maximum threshold of wood mobility. The overall fraction of exported wood decreased with increasing relative size category. The decrease was particularly pronounced in the burned streams, where transport of smaller wood sizes was particularly high, suggesting that potentially mobile wood (i.e. mobile wood in the Large and smaller categories) is easily exported from the burned streams. These findings are similar to findings by Jones and Daniels (2008) that wildfire promotes wood instability in the streams.

Measurements of the decomposition term in the study streams is in conflict with the commonly used assumption that volume loss to decay is negligible over a period of 20-40 years (e.g., Martin and Benda, 2001; Benda et al. 2002, Benda et al. 2003). Our findings suggest that volumetric loss to decay is in fact measureable and in some cases significant over study periods as short as 4 years. Decomposition was found to be, on average, a third of the volume of fluvial export. The half life of wood based on values of decomposition was calculated to average 71 years, which is consistent with findings by Chen et al. (2005) for streams in the Okanagan basin, although Chen et al. (2005) were measuring gravitational decay through chemical breakdown rather than volumetric decay. Jack Creek displayed a higher decomposition rate than the other streams relative to the total volume of wood in the stream. This is may be attributed to the high export rates at Jack Creek, and the associated high mechanical breakdown of wood in the channels.

2.4.3 Storage term

By affecting the input term of the budget, riparian disturbances were found to significantly influence the net accumulation or depletion of wood at the study sites. Storage rates at the reference sites are either close to zero or slightly negative. McDougall, with a high depletion rate, has high fluvial exports and imports, and large volumes of wood in the channels which may be an indication of a previous episodic event upstream that increased LWD loading. Storage rates are, on average, larger and positive at the disturbed sites. Fire sites have the highest storage rates, regardless of stream size and LWD export. At the MPB sites, positive storage was to be expected given the low export rates from these smaller streams. Individual pieces of wood at MPB sites can be expected to remain in storage for some time due to low export rates, and decomposition will be the main output mechanism. Wood recruitment rate at the MPB sites is expected to climb steadily for the next 30-40 years, and recruitment should continue to increase at the burned sites until a peak in approximately 30-40 years (Bragg, 2000). At the burned sites, this will be offset to some degree by high transport rates. However, at the MPB sites, wood loading will increase dramatically and individual recruits will have very high residence times.

2.5 Summary and management implications

The findings presented in this study provide a complete, detailed wood budget of the headwater streams in the Okanagan Basin, built on empirical measurements of each component. Using the wood budget framework, we are able to summarize some of the impacts of fire and Mountain Pine Beetle to the loadings and characteristics of LWD in the study streams. At the reference sites (both fire and MPB references) that there is a very slow net depletion of wood in the stream channel. Fires increase the volume of wood recruited to the streams through riparian processes and may increase rates of bank erosional inputs in larger streams, and decrease the amount of wood recruited through exhumation. MPB infestation appears to slightly, but not statistically significantly increase wood recruitment from riparian sources. There has been a shift in recruited wood at streams with riparian disturbances towards the largest relative size classes, as per Hassan et al. (2005). Our wood budgets suggest that volumetric decay should not be disregarded, and that volumetric loss to decay is in fact measureable over study periods as short as four or five years.

The matrix of relative wood sizes defined by Hassan et al. (2005) was found to be a valuable predictor of wood stability, and facilitated the direct comparison of wood stability and size at streams of different sizes. However, truncating our sampling of wood at lengths of 1m and diameters of 10cm limited our ability to compare streams of small sizes as it under represented small and intermediate sized wood for the smaller streams. The higher rate of recruitment at the MPB sites is potentially a product of intensive salvage logging on one or both sides of the buffer strip at these streams. Recruitment rates are expected to increase at both the fire and the MPB sites over the next several decades.

Mitigating the impacts of forest disturbance on aquatic ecosystems is an important task for forestry planners, and relies on accurate quantification of the potential impacts. Our findings demonstrate that elevated levels of LWD recruitment can be expected within two years of a wildfire, and result in increased storage regardless of stream size (up to the 7m investigated in this study). The effects of MPB on wood recruitment are slower to develop than fire, but may be accelerated by the widespread salvage logging occurring in the central interior, exposing riparian buffer strips to adjacent cutblocks with high winds and variable weather. Considering the vulnerability of MPB-killed trees to windthrow, riparian buffers that are left to protect streams from the effects of salvage logging may need to be wider than buffers prescribed for living, healthy trees under normal circumstances. Downstream communities should anticipate increased levels of LWD export from affected watersheds over the next several decades, particularly associated with high discharge years, and prepare to mitigate potential infrastructural impacts (e.g., Fremier et al., 2010).

Chapter 3: The influence of LWD on the sediment dynamics of low-sediment supply streams in the Okanagan Basin, British Columbia

3.1 Context and background

Over the past several decades, extensive research has documented the geomorphic role of Large Woody Debris (LWD) in fluvial environments. Studies in the Pacific Northwest have found that LWD is the causative agent for up to 90% of pools (e.g., Carlson et al., 1990; Montgomery et al., 1995; Buffington et al., 2002; Chen et al., 2008), causes significant elevation loss in a given reach (Faustini and Jones, 2003), stores sediment through the formation of steps, the accretion of bars and discrete sediment deposits (Keller and Swanson, 1979; Bilby and Ward, 1991; Gomi et al., 2001) and significantly increases in-stream resistance causing overall fining of channel substrate by reducing effective boundary shear stress (Buffington and Montgomery, 1999a; Curran and Whol, 2003; Manga and Kirchner, 2000). Streams with high LWD loading have greater habitat complexity (Ralph et al., 1994) and support greater biodiversity compared to streams with low LWD loading (Wondzell and Bisson, 2003).

The effects of LWD on channel morphology vary spatially, and depend on the underlying geomorphic and sedimentological characteristics of a stream, as well as the loading and characteristics of the wood itself. In high-sediment supply streams, sediment dynamics have been shown to be strongly influenced by the magnitude and frequency of flood events (Wolman and Miller, 1960). The effects of LWD are generally less important in these streams, and readily available sediment supply may obscure the effect of LWD on channel morphology (Faustini and Jones, 2003). In supply limited channels, sediment dynamics are complicated by well developed surface structures, armoured beds, complex combinations of sources of resistance and the sediment/discharge relationships are not universally applicable (Hassan and Zimmerman, 2011). Compared to larger, higher order streams where wood is more easily transported and sediment is readily abundant from bank erosion and upstream sources, the relative importance and complexity of LWD-related storage is thought to be highest in these supply limited, low order streams where LWD supplements alluvial sediment storage sites (Keller and Swanson, 1979; Bilby and Ward, 1991; Massong and Montgomery, 2000; May and Gresswell, 2003). Because of the role of LWD in sediment storage in small streams, it is often assumed that additions of LWD increase sediment heterogeneity. However, the assumption needs to be tested in sediment-supply limited channels.

Our understanding of wood-related sediment storage in low order streams is mainly derived from studies of pool-riffle streams (Smith et al., 1993; Buffington and Montgomery, 1999a and b; Manga and Kirchner, 2000; Curran and Wohl, 2003; Klaar et al., 2011), headwater streams with debris flow inputs of LWD and sediment (Nakamura and Swanson, 1993; May and Gresswell, 2003), or low gradient streams (Massong and Montgomery, 2000; Klaar et al., 2011). Recent research suggests that the complex sediment transport regimes of steep, coarse grained streams may be highly influenced by LWD dynamics (Faustini and Jones, 2003; Benda et al., 2005, Hassan and Zimmerman, 2011). However, further research is needed to assess the quantitative role of LWD in sediment storage and to test the commonly held assumption that LWD determines sediment diversity and dynamics in headwater streams. Specifically, the relationships between LWD and sediment diversity and dynamics observed in supply-rich streams need to be tested under opposite conditions of low-sediment supply. Furthermore, whereas extensive research on the impacts of logging has documented changes to post-harvest habitat quality (e.g., Hogan 1986; Carlson et al. 1990, Bilby and Ward, 1991; Richmond and

Fausch 1995), the impacts of natural riparian disturbances in headwater systems remains an important research gap.

In this study, we measured LWD-related sediment storage and related it to wood density, stability and function in a range of sediment-supply limited headwater streams in the Okanagan Basin, British Columbia. Our streams covered a range of channel morphologies and wood loadings, and we contrasted our data to the data from high sediment supply streams in Alaska and the Olympic Peninsula, as presented by Buffington and Montgomery (1999a). Whereas Buffington and Montgomery (1999a) found a strong positive correlation between wood loading, sediment diversity and substrate fining in high-sediment supply streams, we assessed any similarities or differences in the nature of these LWD-sediment interactions under conditions of low-sediment supply in the Okanagan streams. Specifically, we assessed the volumetric storage of sediment by LWD and any associated changes to substrate size and diversity. We included three recently (<6 year) burned streams in our analysis to investigate any associated changes to LWD-sediment interactions.

3.2 Methods

3.2.1 Site selection and description

The study area is located in the southern central interior of British Columbia in the Okanagan Basin. The Okanagan Basin is located on the Thompson Plateau, in the rain shadow of the Cascade Mountain Range that lies to the west, and with the Monashee Mountains to the East. As a result of the rainshadow effect, the Okanagan has a semi-arid climate, with mean annual precipitation ranging from 250mm in the valleys to over 1000mm in the alpine and subalpine areas, and with a mean annual temperature between 1.7 and 4.7ºC (Cohen and Kulkarni, 2001). Annual streamflow follows a snow-melt dominated hydrologic regime, with freshet occurring between April and July (Canada-British Columbia Okanagan Basin Agreement, 1974). The basin has an average elevation of approximately 1120m, and is characterized by a high plateau between 1000 and 1800 m (Scherer and Pike, 2003). Geologically, its surficial deposits are dominated by post-glacial deposits, with unconsolidated glacial till with numerous bedrock outcrops and thin morainal veneers (Roed, 1995). There are a number of biogeoclimatic zones in the basin, ranging from a Bunchgrass zone in the hot, dry valley bottoms to Montane Spruce and Engelmann Spruce-Subalpine Fir at higher elevations, where temperatures are generally cooler and the climate becomes wetter (Scherer and Pike, 2003).

The study sites were part of a long term study on the impacts of fire, and were established in paired sets of three burned and three undisturbed streams in the of Interior Douglas Fir (IDF) and an additional six unburned streams in the Montane Spruce (MS) biogeoclimatic zone, for a total of 12 study streams. The initial study reaches, 100m in length, were expanded in 2009 to 30-50 channel widths to conduct a detailed morphological assessment that conformed to the minimum reach length identified by Scherer (2008). Table 3.1 summarizes reach characteristics for the study streams. The selection of the sites is described above in Chapter 2. A map of their locations is also shown in Chapter 2 (Figure 2.1).

Table 3.1: Reach characteristics of the study reaches

Stream	Basin area (km^2)	average width (m)	Reach length (m)	Gradient (%)	D_{50} (mm)	Total LWD ($m^3/100m^2$)
Bellevue*	71.85	7.69	380	4.46	90	0.99
Deeper*	16.24	4.16	176	5.90	64	2.12
Goode*	9.63	2.68	103	3.37	64	2.28
Jack	30.40	4.24	212	7.16	128	0.63
McDougall	20.47	3.67	243	6.19	64	2.4
Greata	1.51	2.67	131	2.10	22.6	1.05
Beak	9.87	2.13	103	6.45	128	0.41
Mellin	9.56	1.61	96	3.20	90	1.58
Cotton	1.85	2.26	103	7.28	32	1.43
Upper P	5.06	2.94	148	4.43	90	1.38
Trout	3.97	2.12	97	2.58	16	0.96
Pennask	13.03	3.72	172	2.59	64	0.97

* Indicating streams burned in the 2003 Okanagan Mountain Park fire.

The streams in this study represent a range of substrate and channel types, shown in Table 3.3. Two of the streams had gravel beds (as defined by the Wentworth scale in which gravel sized sediment is between 4 and 64mm in diameter) and were pool riffle systems (Trout and Greata Creeks). Two of the reaches, Beak and Mellin Creeks, are narrow, high gradient, cobble-bedded systems with a semi-alluvial step-pool morphology. Cotton Creek is a gravel bed system, with a high gradient step-pool morphology in the upper half of the reach and a low gradient pool-riffle system in the lower half of the reach. The other seven study streams are cobble-bedded, alluvial step-pool streams, covering a narrow range of widths and gradients. Based on a lack of mass movement inputs, limited bank erosion, armoured beds and their step pool morphologies, we determined all the study streams to be low sediment supply systems, with the exception of the three gravel bed streams (Trout, Greata and Cotton Creeks). Figure 3.1 shows examples of a pool-riffle system, a semi-alluvial system and a step-pool system.

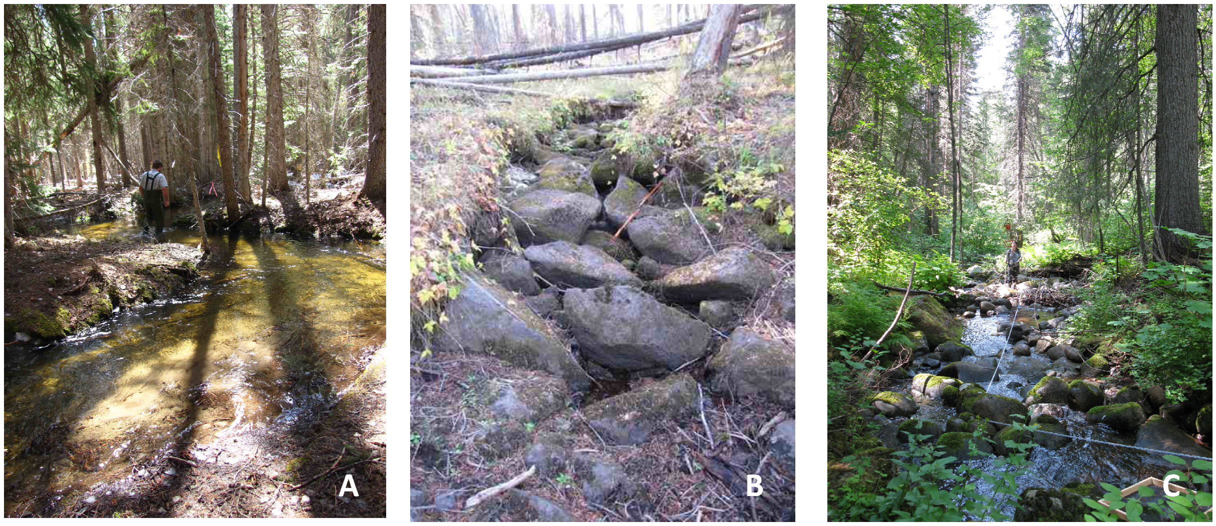

Figure 3.1: Examples of the different stream types. A) Trout Creek, a well developed pool-riffle stream with gravel sized substrate, B) Mellin Creek, a semi-alluvial reach with non-alluvial step-pool development and C) Jack Creek, a cobble bed reference stream with a developed alluvial step-pool morphology.

3.2.2 LWD data collection

LWD and morphological surveys were carried out using a Leica TPS800 total station. At each stream reach, LWD (defined in this study as all pieces of wood over 10cm in diameter and 1m in length) was tagged using a uniquely numbered metal tag secured to the logs with wire. Manual surveys were conducted of the large and small end LWD diameters using callipers, of the submergence category as per Chen et al. (2008), and of the morphological functioning of each piece (see Table 3.2 for a summary). A total station was used to determine the coordinate of each in-stream end (whereby the stream perimeters were defined as bankfull width). Wood length was derived from the total station coordinates of the piece ends, and volume was calculated using the formula for a tapered cylinder, as per Chen et al. (2005). Orientation to flow was derived from digitized thalweg profiles (see: 3.2.3 Channel Surveys below) and digitized LWD polylines in ArcGIS 9.3. Wood budgets were built based on repeated annual surveys of wood in the initial 100m reaches, and are presented in Chapter 2.

Table 3.2: Summary of the criteria used in the LWD characteristic surveys

Characteristic	Classification
Function	1. Step forming
	2. Pool forming
	3. Sediment storage
	4. Bank stabilization
	a) Stabilizing
	b) Destabilizing
	5. Bracing other pieces
	a) of LWD or b) of FWD
Submergence	6. Lower half of bankfull height
	7. Upper half of bankfull height
	8. Spanning the channel cross section
	9. Partially buried
	10. Any combination of the above positions

Functional wood in the streams was defined as wood that was observed to interact with flow to alter channel morphology, either through sediment storage, pool formation, bank stabilization or destabililzation, and/or step formation. Streams were determined to be wood-rich or wood-poor both in terms of total and functional wood density, as reported in Table 3.3. The threshold between wood-rich/poor was the median wood loading for the Okanagan streams, as per Buffington and Montgomery (1999a), for both functional and total wood loadings. LWD stability was determined from the repeated yearly surveys. Wood stability was represented by an index of wood stability; the ratio of the total number of wood pieces present in the first year of the study (Lt) that were exported over the course of the study (Lm).

3.2.3 Channel surveys

A Leica TPS800 was used to conduct channel surveys of each of the reaches. Thalweg profiles were made through measurements every 1m. Channel cross sections were conducted as necessary to capture channel variability with, in the absence of much cross sectional variation, a maximum spacing of 10m. To conduct sediment surveys, the stream bed was visually divided into distinct textural patches of homogenous sediment, called facies. Detailed sediment facies maps were produced for each of the streams by surveying the spatial extent of each sediment facies with the total station and by conducting Wolman pebble counts (n=100) for each of the facies (Wolman, 1954). The median grain size (D_{50}) of each facies was derived from the Wolman pebble count for that facies (Wolman, 1954). Wolman pebble counts were not done for every facies; where substrate was too fine to measure (<4mm), substrate composition was visually estimated using the methodology presented in Buffington and Montgomery (1999c). The area of each facies (as calculated in ArcGIS 9.3) was used to weight the substrate size of each facies and produce an overall 'weighted' D_{50} for each stream segment based on the relative spatial coverage of different substrate sizes.

3.2.4 Analysis of sediment storage

Sediment diversity was estimated using the absolute number of facies (as per Buffington and Montgomery, 1999a) scaled by channel width (facies/cw). The volumetric storage of sediment was derived from the long profiles of the streams. A polynomial line of best fit was applied to each of the long profiles. Lengths of the thalweg long profile above the best fit line therefore represent areas of sediment storage, and lengths below the line represent to be scour (Luzi, 2000). Sediment volume was calculated by multiplying the vertical area of sediment above the best fit line by average channel width. The locations of LWD that had been identified in the field as being functional for sediment storage (i.e. was observed to store sediment upstream) were plotted on the long profiles, and sediment storage immediately upstream of those pieces was considered to be sediment storage attributable to LWD.

Predicted D_{50} was compared to measured D_{50} using the methodology of Buffington and Montgomery (1999a), whereby theoretical D_{50} is derived from the Du Boys and the Shields equations as described below:

$$D_{50} = \frac{\rho g h \square S}{\tau^*_{c50}(\rho_s - \rho) g} \qquad 1)$$

whereby ρ and ρ_s are the fluid and sediment densities (1000 and 2650 kg/m^3, respectively), τ^*_{c50} is the dimensionless critical shear stress for incipient motion set to 0.030 (suggested by Buffington and Montgomery,1997; 1999a), g is gravitational acceleration (9.81m/s^2), h is the bankfull hydraulic radius and S is channel slope. The top term of the fraction is equivalent to bankfull sheer stress, τ_o, which was calculated for each of the study reaches. The predicted value of D_{50} was compared to observed values of D_{50} in the streams as an indication of sediment fining, and degree of fining was explained in terms of wood loading.

Buffington and Montgomery (1999a) compiled sedimentological data from a range of Alaskan streams ranging in width from 4.6m to almost 30m, and from streams in the Olympic Peninsula of Washington ranging in width from 5.12m to 13.39m. All of the streams had gradients less than 0.027. Most were gravel bed streams, although some were cobble bedded. The streams had pool-riffle morphologies indicative of high sediment supply. We contrast our data directly with theirs to illustrate differences between the low-sediment supply, coarse grained Okanagan streams and high-sediment supply systems. It should be noted that based on differing median wood loadings for each of the systems, the distinction between wood rich and wood poor (based on median wood loadings) varies by region.

3.3 Results

In this section we first present the sediment storage volumes and diversity of the study streams. We present examples of LWD-related sediment storage in the channels and then quantify the volume of sediment stored by LWD and the impacts of LWD on sediment fining. We relate LWD function to wood density and explore the relative importance of total versus functional wood density as a predictor of the role of wood in these low sediment supply streams. Throughout the analysis we use data from Buffington and Montgomery (1999a) and Wood-Smith and Buffington (1996) to contrast the role of LWD between low and high sediment supply streams.

3.3.1 Sediment storage and characteristics

The average volume of sediment stored in the channels was $0.05m^3/m^2$, ranging from $0.03m^3/m^2$ at Pennask Creek to $0.08m^3/m^2$ at Deeper Creek (Table 3.3). Developed bars and distinct sediment deposits were rare in the study streams, and contributed to sediment storage only in some of the streams. Alternating bar sequences were only found in the two pool-riffle streams, Trout and Greata Creeks. Along the thalwegs of the streams, the depths of sediment storage ranged from 7cm at Pennask Creek to 18cm at Jack Creek. The volume of sediment stored in the streams was significantly influenced by the channel width ($p < 0.01$), such that larger streams stored significantly more sediment per square meter than their smaller counterparts (Figure 3.2a). Two of the burned streams (Goode Creek and Bellevue Creek) fit well within this trend, although Deeper Creek was well above the line. Pennask Creek stored substantially less sediment than predicted, and did not fit well with the overall trend.

The number of facies per channel width (cw) was an average of 0.96/cw, and was highly variable, ranging from 0.35/cw at Mellin, to 1.5/cw at Pennask. There is a weak but significant relationship between channel width and the number of facies per channel width (Figure 3.2b). Bellevue Creek, a burned stream, does not fit with the overall trend. Gradient and shear stress were not significantly related to sediment storage volume or the number of facies per channel width.

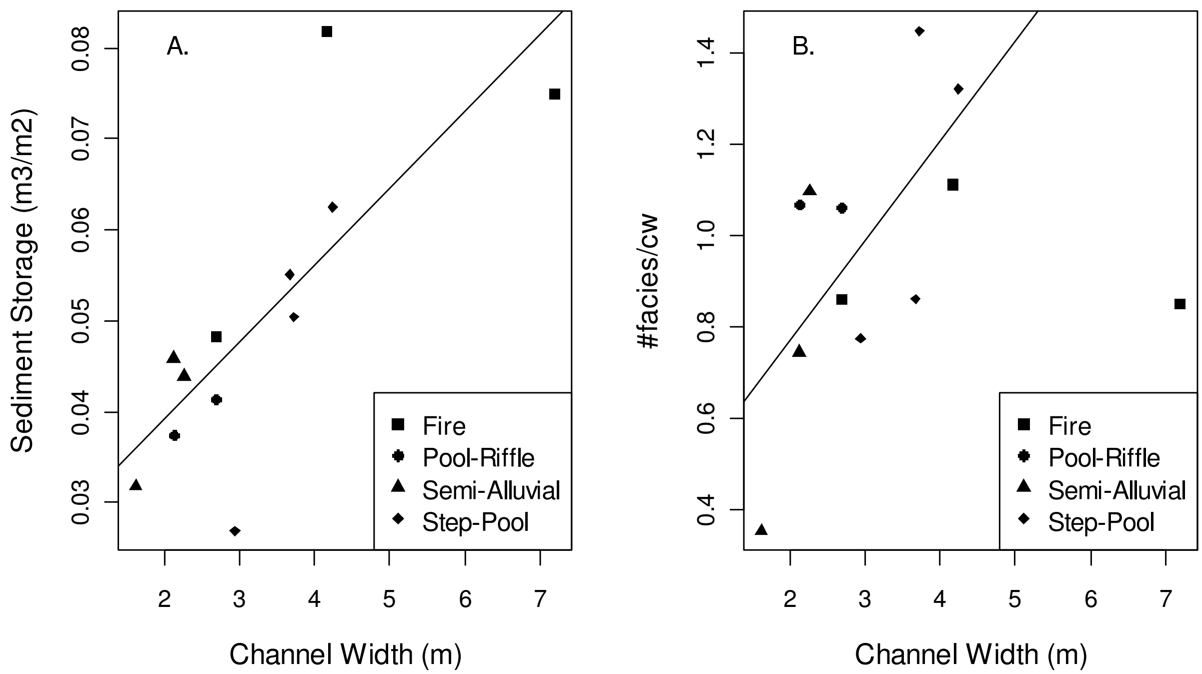

Figure 3.2: The relationship between channel width: A) the volume of sediment stored in the channels (*p* <0.01, R^2 = 0.56), and B) the number of facies per channel width (cw) (*p* < 0.05, R^2 = 0.37; excluding Bellevue, the one outlier)

Table 3.3: Sediment storage and wood loading characteristics of the 12 study streams

Stream	Sediment stored behind LWD (m^3/m^2)	% total sediment storage by LWD	% LWD -related sediment storage in bars	Substrate type	Functional wood loading*	Total Wood loading*	Channel Type
Bellevue[a]	0.011	14.16	0.0	Fine cobble	poor	poor	step pool
Deeper[a]	0.004	4.91	48.0	Fine cobble	poor	rich	step pool
Goode[a]	0.000	0.00	N/A	Fine cobble	poor	rich	step pool
Jack	0.032	50.99	3.4	coarse cobble	rich	poor	step pool
McDougall	0.042	76.70	9.3	Fine cobble	rich	rich	step pool
Greata	0.032	76.45	0	gravel	rich	poor	pool riffle
Beak	0.000	0.00	N/A	coarse cobble	poor	poor	semi-alluvial
Mellin	0.000	0.00	N/A	Fine cobble	poor	rich	semi-alluvial
Cotton	0.003	7.94	77.0	gravel	poor	rich	semi-alluvial
Upper P	0.025	93.75	3.0	Fine cobble	rich	rich	step pool
Trout	0.034	91.67	6.0	gravel	rich	poor	pool riffle
Pennask	0.026	52.46	4.5	Fine cobble	rich	poor	step pool

* Where the threshold between rich and poor wood loading is based on the median loading values, as per Buffington and Montgomery (1999a).

[a] indicates burned streams

3.3.2 LWD function

The median total wood loading in the study streams was 0.15 pieces/m^2 (1.21m^3/100m^2), almost five times higher than the wood loading in the Alaskan and Olympic Peninsula streams (Wood-Smith and Buffington, 1996; Buffington and Montgomery, 1999a). The loading of functional wood in the channels was variable, and in all but three streams less than half of the total wood load was considered functional in terms of sediment storage, creating pools, stabilizing or destabilizing channel banks or causing steps. In Jack, Trout and Pennask Creek between 60 and 90% of the wood load was functional. The ratio of functional to total wood was significantly ($p < 0.05$) lower in the burned streams than in the unburned streams (22% relative to 58%).

The median loading of functional wood was 0.03 pieces/m^2, or 0.41m^3/100m^2, identical to the total wood loading reported by Wood-Smith and Buffington (1996) and Buffington and Mongomery (1999a). Of the six streams considered to be “Functional Wood-Poor”, three were the burned systems, and the remaining three were Beak, Mellin and Cotton Creeks, the semi-alluvial channels (Table 3.3). When classifying streams into wood-rich or wood-poor based on the median value of total wood loading, however, the pattern of wood-rich/poor is substantially different, and the only “Functionally Wood-Poor” stream that is also “Total Wood-Poor” is Bellevue Creek. Thus, although some of the streams may have had high total wood loading, they were comparatively poorer in functional wood than other streams that had lower total wood loading (e.g., Mellin Creek, Cotton Creek, see Table 3.3).

LWD provides important structures that influence sediment storage through two primary mechanisms: the formation of sediment wedges upstream of channel spanning jams, and through the nucleation of discreet bars and deposition zones created by small jams and isolated pieces. The maps in Figure 3.3 illustrate typical LWD jam-related sediment storage in the study streams.

As shown in Figure 3.3, stable jams of LWD caused particularly large sediment storage areas upstream and associated sediment depravation downstream.

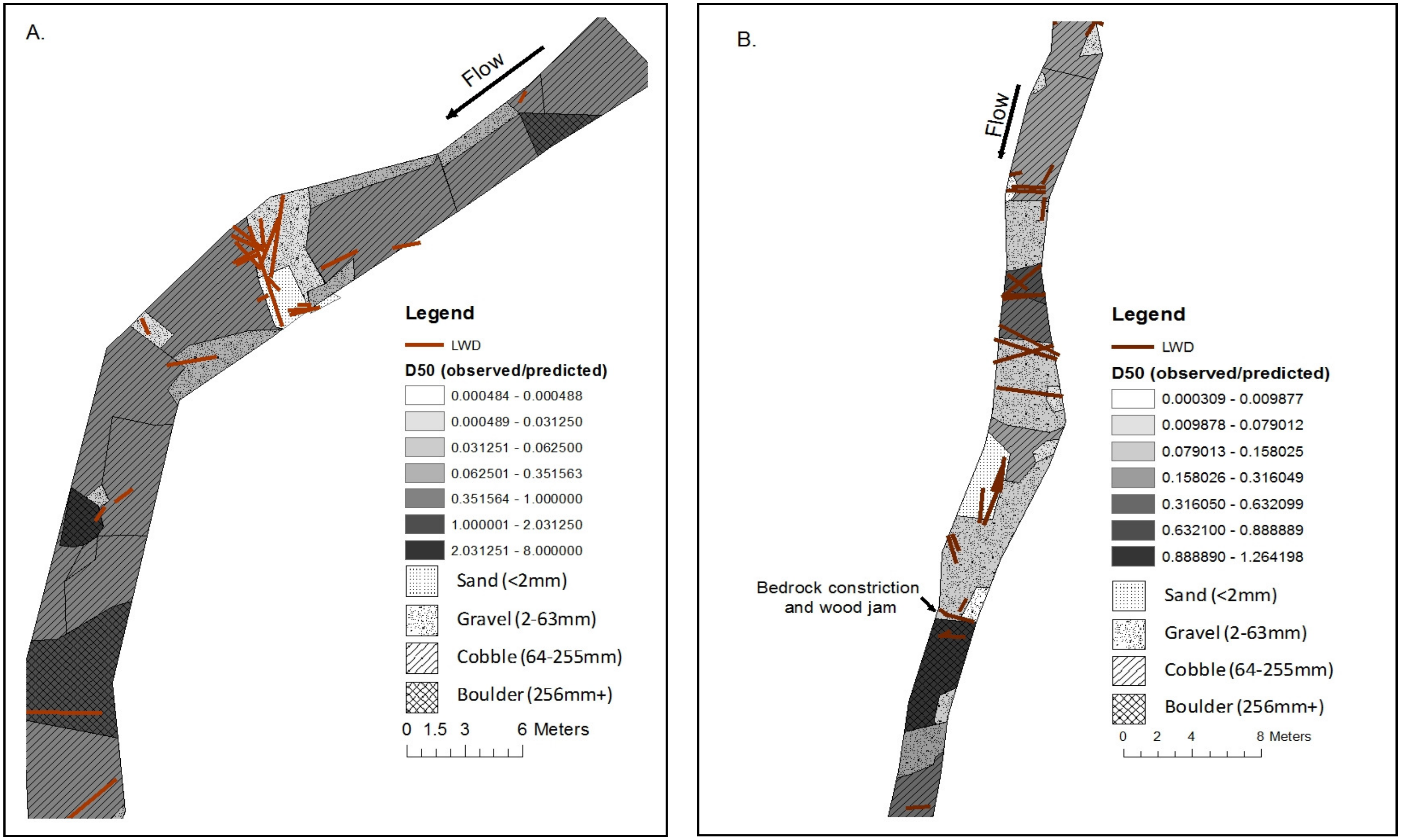

Figure 3.3: Two examples of step-pool morphological streams with high functional wood loading: a) Jack Creek, and b) Upper Penticton Creek

Volumes of sediment stored behind LWD structures (from long profiles as well as the volume of sediment in bars) ranged from 0.0 m^3/m^2 at Goode, Beak and Mellin Creeks to 0.04m^3/m^2 at McDougall Creek. Sediment stored behind LWD comprised between 0% of total sediment storage at Goode Creek, Beak Creek and Mellin Creek to highs of over 90% at Trout Creek and Pennask Creek (Table 3.3). In streams with high volumes of LWD-associated sediment storage, less than 10% of LWD-related sediment storage was stored as bars, and the majority was stored behind large, isolated channel spanning wood jams (Figure 3.4). In Deeper and Cotton Creeks, however, where wood-associated sediment storage is low, between 58 and 77% of LWD-related sediment was stored behind individual pieces of small jams. In general, although the absolute number of large jams storing sediment did not greatly exceed the number of small jams or isolated pieces storing sediment in the streams, the volumes of sediment stored behind large jams were clearly higher, even in cases where the number of individual pieces clearly exceeded the number of large, channel spanning jams (e.g., Upper Penticton, Figure 3.4).

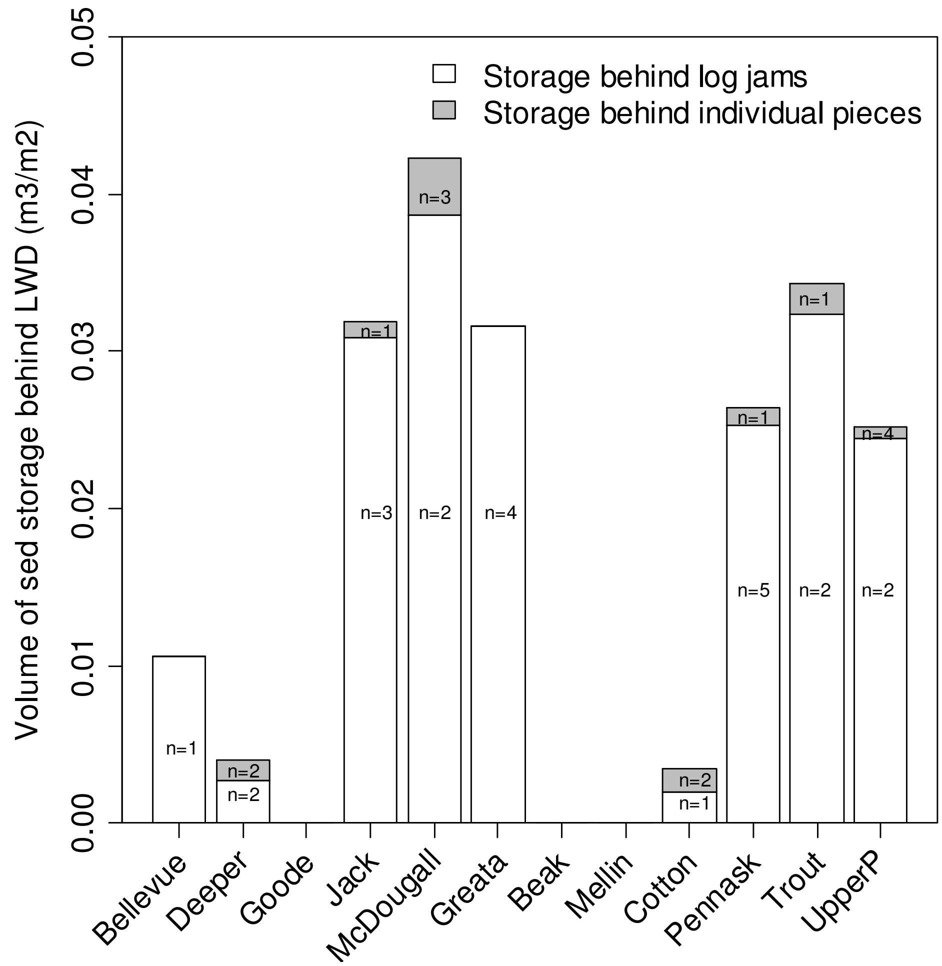

Figure 3.4: The volume of sediment stored behind LWD at each of the streams, broken down by the volumetric contribution of sediment stored behind channel spanning jog jams, and the volume stored behind individual pieces or small jams (Note that the "n" notation refers to the number of jams or pieces contributing to the sediment storage)

Although LWD stored large volumes of sediment in the channels, there was no statistical relationship between total or functional wood density and the total volume of sediment stored in the study streams (Figure 3.5A and B). With two exceptions (McDougall Creek and Beak Creek), there appeared to be a negative relationship between the total volume of wood in the channels and the volume of sediment stored by LWD (Figure 3.5C). This trend was set primarily by the burned streams with high total wood loading and low volumes of LWD-associated sediment storage. However, when only the density of functional wood was considered, both outliers (McDougall and Beak Creek) fit into a significant positive relationship between the volume of sediment stored by LWD and the density of functional wood (Figure 3.5D). Thus, although the total volume of sediment per square meter in the channels was controlled by channel width rather than wood loading, increasing the volume of functional wood in the channels did increase volume of sediment per square meter being stored behind wood structures. Furthermore, comparing total wood loading to sediment storage misrepresented the relationship between LWD and sediment storage.

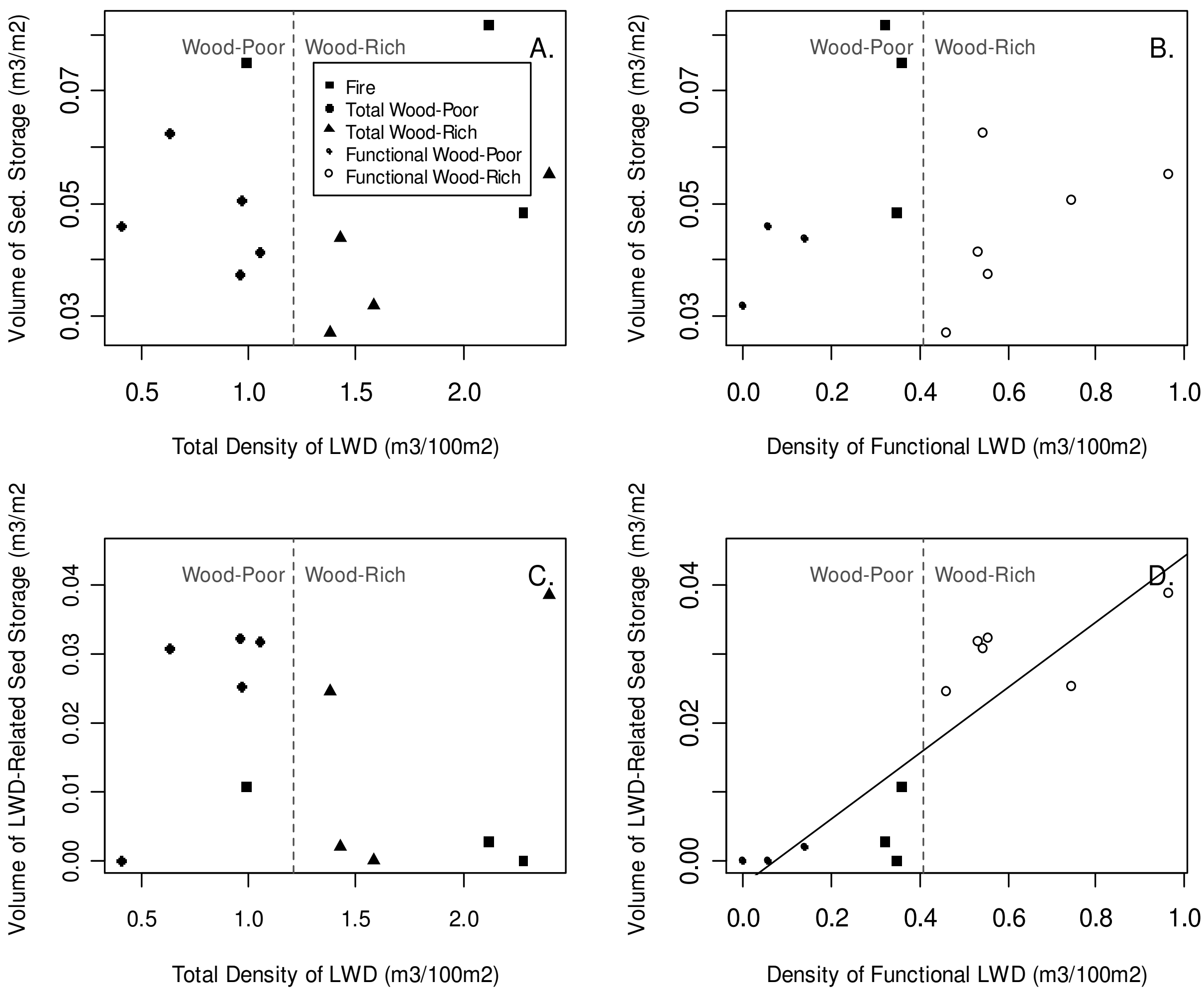

Figure 3.5: The relationships between A) the total volume of sediment in the channels and the total density of LWD, B) the total volume of sediment in the channels and the density of only functional LWD, C) the volume of LWD-related sediment storage and the total loading of LWD, and D) the volume of LWD-related sediment storage and the density of only functional LWD (p < 0.001, R^2 = 0.73) (Note that graphs A and C are segregated into wood-rich and wood-poor based on total wood loadings, and graphs B and D are segregated based on only functional wood loadings)

The sediment diversity or the number of facies per channel width was found to be unrelated to the total wood loading in the channels, and there was only a slight (but not significant) relationship to functional wood loading. Figure 3.6 plots data from the Okanagan study streams data relative to the data from the Olympic Peninsula streams studied by Buffington and Montgomery (1999a). When total wood loading is considered (Figure 3.6A), the Okanagan streams plot substantially lower on the graph than the Olympic Peninsula streams. When only functional wood is considered (Figure 3.6B), wood loadings in the Okanagan streams are closer to those in the Olympic Peninsula ones. Nonetheless, most of our data are located near the lower envelope of the Olympic Peninsula data. The lower sediment diversity may reflect the lower sediment supply in the Okanagan streams, and the lack of a relationship suggests that under low sediment supply conditions, LWD does not act to increase sediment diversity by forming additional textural patches.

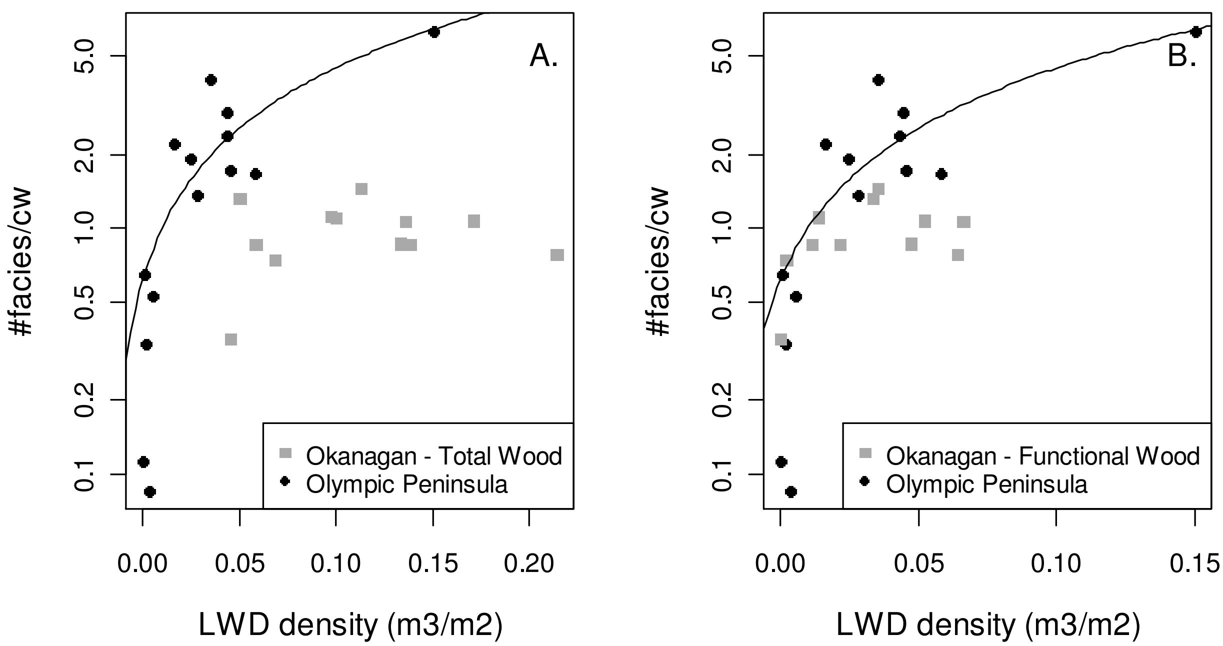

Figure 3.6: The relationship between the number of facies per channel width and the wood density in the Olympic Peninsula streams in Buffington and Montgomery (1999a) and A) the total wood loading in the Okanagan study streams and B) the functional wood loading in the Okanagan study streams (Note that the Olympic Peninsula wood loadings in both a) and b) are total wood loading, as they were not segregated into functional vs. total)

With three exceptions plotting low in the graph (Cotton, Greata and Trout Creeks), the observed D_{50} values in the Okanagan streams relative to shear stress plotted closer to the predicted values than the Olympic Peninsula or Washington streams (Figure 3.7). Allowing for significant variation and small replicate size there does appear to be some stratification in the Okanagan stream data relative to wood loading. Our data suggests that the functional wood-poor streams were the closest to the predicted values, followed by the wood rich streams, and finally the burned streams plotted the furthest away. Overall, however, the low-sediment supply channel plot closest to the theoretical competent D_{50}, whereas the three high-sediment supply Okanagan streams plotted slightly above the Alaskan wood-rich streams.

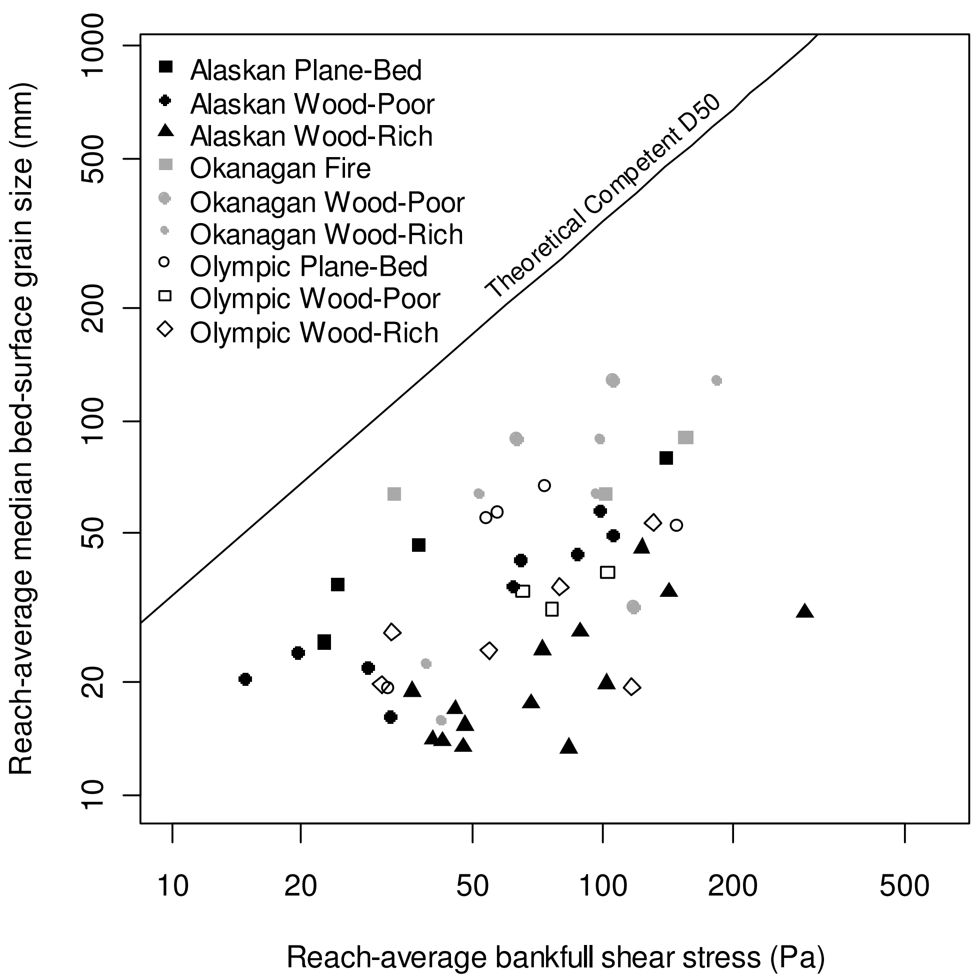

Figure 3.7: The relationship between reach averaged, measured D_{50} in the Alaskan streams from Wood-Smith and Buffington (1996), the Olympic Peninsula streams from Buffington and Montgomery (1999a) and the Okanagan study streams, segregated by functional wood loading (functionally wood-poor or rich) and presented relative to the theoretical competent D_{50} (Equation 1)

Figure 3.8 presents the ratio of observed to predicted D_{50} for the (A) Olympic Peninsula, (B) Alaskan, and (C) Okanagan streams, stratified by wood loading. The plane bed channels in Figure 3.8(B) were streams with low wood loading, simple channel geometries and low hydraulic resistance. Streams with lower ratios represent streams with greater sediment fining. Within each of the geographic locations, there were no significant differences in the ratio of observed to predicted D_{50} between wood loading categories. Nonetheless, there are trends that are persistent between geographic locations. Both the Okanagan and the Alaskan streams display a statistically insignificant decrease in the ratio of observed to predicted D_{50} between wood-poor and wood-rich channels. The most pronounced difference between wood-rich and wood-poor streams was in the Alaskan streams, followed by the Okanagan streams. In the Okanagan streams, the ratio of observed to predicted D_{50} for the burned streams is closer to the functional wood-rich category. The burned streams, although presented separately here for illustration purposes, were also functionally wood poor (Table 3.3).

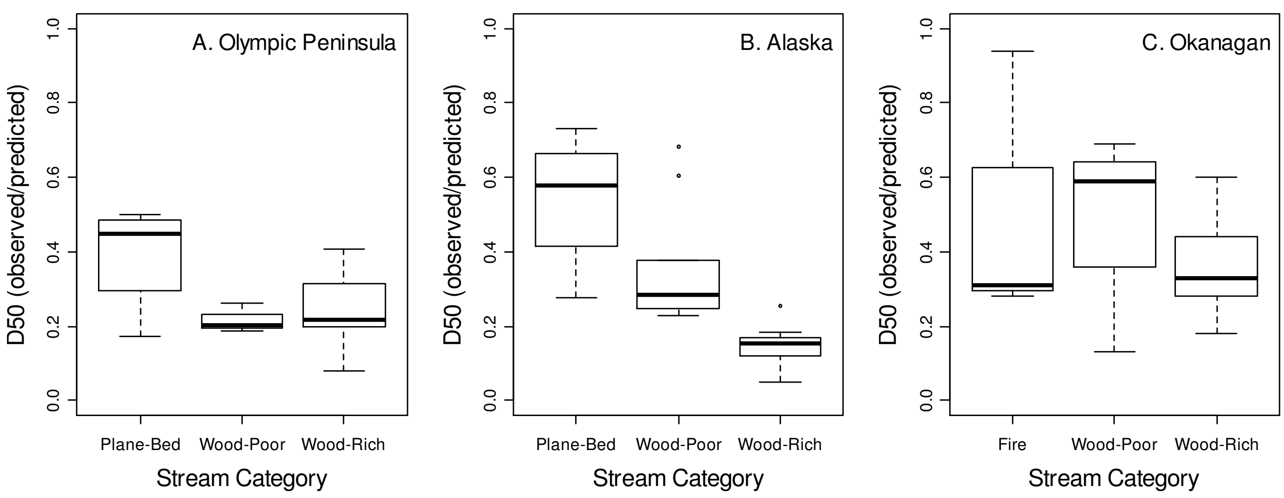

Figure 3.8: The ratio of observed to predicted (as per Equation 1) D_{50} for A) streams in the Olympic Peninsula (Buffington and Montgomery (1999a)), B) streams in Alaska (Wood-Smith and Buffington (1996)), and C) streams in the Okanagan Basin (Note that the Okanagan streams are divided into functional wood rich or poor rather than total wood rich or poor)

The functionality of wood in the channels was highly dependent on the wood stability (Figure 3.9A). For streams with a 1:1 ratio of mobile to total wood (Lm/Lt), there was almost no functional wood in the channels. Streams with Lm/Lt ratios greater than approximately 0.2 had significantly decreasing functional wood density with increasing wood instability. The three wood-poor streams (Mellin, Cotton and Beak Creeks), however, with highly stable wood (with Lm/Lt less than 0.2) did not fit in with this relationship. They have highly stable wood but almost no functional wood. This can likely be attributed to the high percentage of wood spanning the channel in these three streams (Figure 3.9B). There is a significant negative relationship ($p < 0.05$) between the percentage of wood spanning the channels and the percentage of wood pieces that are functional. When almost none of the wood pieces span the channel, almost all of the wood pieces serve a function (of sediment storage, pool and step formation or bank stabilization/destabilization), although two of the burned streams provide an exception to this trend.

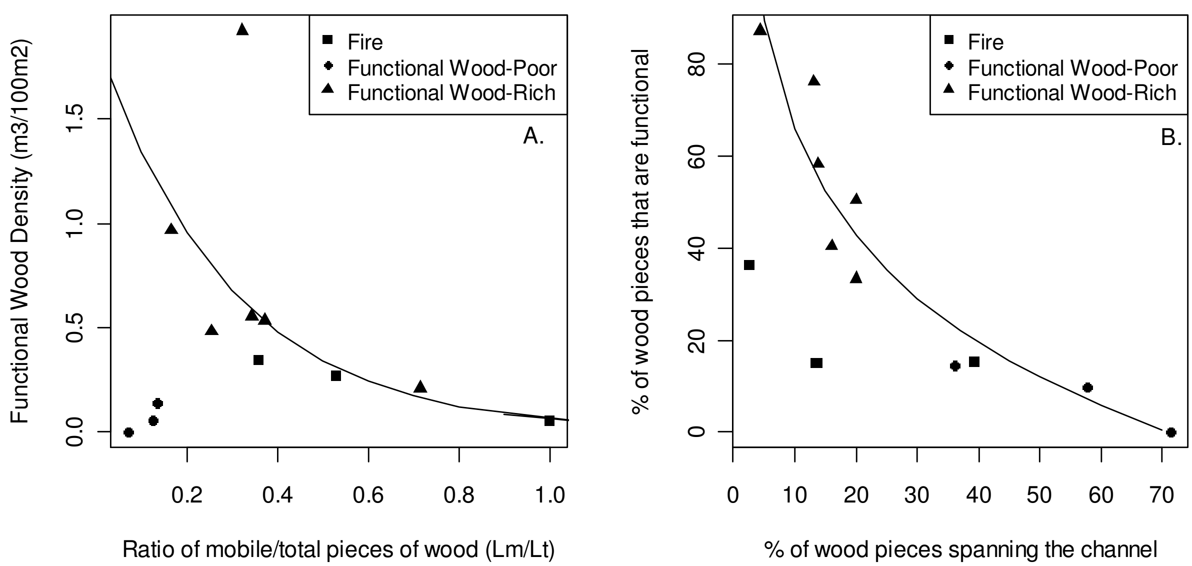

Figure 3.9: The relationship between A) functional wood density and the fraction of 2005 pieces that were exported from the channel (Lm/Lt) ($p < 0.05$, $R^2 = 0.46$; not including functional wood-poor streams) and B) the percentage of wood pieces that were functional and the percentage of wood pieces that were spanning the channel ($p < 0.001$, $R^2 = 0.92$; excluding the Fire streams)

3.4 Discussion

Twelve sediment supply-limited forested mountain streams were investigated in the Okanagan Basin to quantify the volume of sediment stored by LWD, and the influence of LWD on sediment heterogeneity and substrate fining. Data from high-sediment supply Alaskan streams and streams in the Olympic Peninsula (from Wood-Smith and Buffington (1996) and Buffington and Montgomery (1999a), respectively) were used to examine the differing impact of wood in high and low sediment supply systems. Three of these streams have had their riparian zones entirely burned during the 2003 Okanagan Mountain Park wildfire, and the associated impacts to sediment dynamics are considered hereafter.

The Okanagan channels are much smaller than the Olympic Peninsula and Alaskan streams, and represent a completely different channel type. With the exception of two pool-riffle channels, the Okanagan study streams are coarse substrate step-pool or semi-alluvial systems, typical of low sediment supply systems. The Olympic Peninsula and Alaskan streams are larger, generally lower gradient, pool-riffle systems. High-sediment supply in these streams results in sediment dynamics that differ dramatically from those in sediment-limited mountain streams with armoured bed and stable bedforms. The total wood loading in the Okanagan streams is substantially higher than the wood loading in the Olympic Peninsula and Alaskan streams, likely because the loading of wood is known to increase with decreasing channel width (e.g., Bilby and Ward, 1991). However, the loading of functional wood in the Okanagan streams is identical to the total wood loading in the Olympic Peninsula and Alaskan streams. In the sediment rich Olympic Peninsula and Alaskan streams, Buffington and Montgomery (1999a) reported a strong relation between wood loading and sediment diversity, and a significant fining of channel substrate due to high wood loadings. In the Okanagan streams we found LWD to have important effects on sediment storage that resulted in different sediment dynamics than those observed in the Olympic Peninsula and Alaska.

3.4.1 LWD and sediment storage, diversity and fining

The total volume of sediment stored in the streams and the sediment diversity were primarily controlled by channel width, with larger streams having more volume and more diverse sediment. There was no statistical relationship between total sediment storage and either total or functional wood density. LWD was, however, an important mechanism of sediment storage, storing as much as 93% of the sediment volume in the study streams. The volume of LWD-stored sediment increased with increasing density of functional wood in the study streams, where the definition of functional wood included wood storing sediment as well as wood performing other geomorphic roles. As channel width exerted the primary control on sediment volume in the channels, and neither total nor functional wood load had a relationship to sediment volume, it appears that although higher functional wood loads may store a significant proportion of sediment in the channels, under conditions of limited sediment supply they do not alter the absolute sediment storagre beyond the limits determined by channel size/transport capacity. Streams with low LWD loadings do not appear to have lower sediment volumes than would be otherwise predicted from antecedent morphological conditions.

Considering the large percentage of sediment stored by LWD in some of the Okanagan streams (as much as 94% in Trout Creek), it is surprising that there does not appear to be a direct impact by LWD on sediment diversity and the number of distinct sediment facies in the streams, as was found in the Olympic Peninsula streams. As exemplified by the maps in Figure 3.6, functional LWD clearly creates distinct sites of sediment deposition with the largest volumes stored behind few and infrequent channel spanning wood jams, similar to findings by Hassan et al. (2008).

However, this does not appear to translate into elevated reach scale sediment diversity. Studies such as Beschta (1979), Diez et al. (2000), Gomi et al. (2001) and May and Gresswell (2003) suggest that in the absence of LWD, headwater channels would be featureless and essentially lacking in sediment storage. Indeed, the three unburned “Functional Wood-Poor” channels (Mellin, Beak and Cotton Creeks) lacked alluvial bedforms and had semi-alluvial bedforms, supporting the assertions of May and Gresswell (2003) that in headwater streams, functional wood can force the development of an alluvial channel from an otherwise non-alluvial stream. However, in our study streams, this did not translate into a net increase in the number of textural patches in wood-rich channels. Volumes of sediment and sediment diversity were determined by underlying geomorphic conditions such as channel width, and the function of LWD was limited by these conditions.

In the high sediment supply streams in the Olympic Peninsula and Alaska, sediment storage sites forced by LWD would have been supplemented in the rest of the stream by alluvial sediment storing bedforms such as bars. Similarly, Hassan et al. (2008) found that although LWD jams stored large volumes of sediment in infrequent structures in British Columbia’s Carnation Creek, the majority of sediment storage in the streams was in alluvial bars that were more frequent and spaced evenly along the channel. Under these conditions, LWD-sediment storage would have augmented the textural patchiness of the substrate by adding sediment storing bedforms to a pre-existing pattern of alluvial bedform development. However, in sediment-limited streams, large LWD jams that store significant proportions of the sediment in the streams would limit the amount of sediment available for the development of other alluvial bedforms. Thus, additional textural patches created by LWD-related sediment storage would have been offset by the downstream sediment deprivation.

By effectively trapping fine sediment, LWD jams in the Okanagan study streams may deprive the rest of the channel of sediment that could be stored in alluvial bedforms, thus concentrating sediment facies, instead of increasing diversity. These findings are similar to other studies of supply limited systems. Faustini and Jones (2003) found that aggradation in boulder rich, high gradient streams was limited to zones upstream of LWD, and that D_{50} did not vary far from the average in downstream sections with no functional wood. Heede (1985) found that removing log steps from high gradient, coarse substrate streams produced a 200% increase in the number of gravel bars by increasing bedload mobility. Similarly, Smith et al. (1993) found that removal of wood increased bedload and promoted the development of alternating alluvial bars.

Stable LWD in the reference streams, particularly when forming jams, is highly efficient at trapping sediment, and as such does not appear to promote sediment diversity under conditions of low sediment supply. It does, however, appear to contribute to reducing the observed D_{50} of the streams relative to the predicted D_{50}, although the replicate size is too small to draw significant conclusions. Nonetheless, the pattern of D_{50} reduction in functional wood rich versus wood poor streams is consistent with that found by Buffington and Montgomery (1999a). Overall, shear stresses in the Okanagan streams were closer to predicted values for all but the high-sediment supply gravel bed streams. This may be due to lower sediment supply, but likely also reflects the different roughness elements in the cobble-bed, step-pool Okanagan streams relative to the gravel-bed, pool-riffle Alaskan and Olympic Peninsula streams. Whereas hydraulic roughness due to wood has been shown to be of high importance in low-roughness streams (e.g., Manga and Kirchner, 2000; Buffington and Montgomery, 1999a), step-pool channels have highly complex combinations of roughness elements, of which LWD is only a minor contributor, depending on its configuration (e.g., Chin, 2003; Curran and Wohl, 2003).

3.4.2 Functional wood loading versus total wood loading

In studies of the morphological function of LWD, wood loading is generally surveyed and reported in terms of total wood load. However, our findings indicate that in our study systems, considering wood load in terms of total wood density yields very different results than considering only functional wood load. Despite high total wood loads in the Okanagan streams relative to the Olympic Peninsula and Alaskan streams, only an average of a third of the wood was functional, and considering total wood load did not yield meaningful relationships to sediment dynamics. Although determining total wood loading may be important for other purposes, studies of wood function need to distinguish between functional and total wood loads to draw meaningful relationships.

Wood function in the study streams was found to be highly dependent on wood stability, suggesting that stable wood is more likely to become functional. However, considering the importance of channel spanning jams in storing sediment (as reported here and elsewhere, e.g., Abbe and Montgomery, 1996; Faustini and Jones, 2003; Hassan et al. 2008) there must be sufficient mobility to redistribute wood to stable locations where it interacts with the channel and other wood pieces. In our study, we found that there was a minimum threshold of mobility beyond which the three most wood-stable streams in the study had little to no functioning wood. These three streams were three of the smallest streams in the study, and also received the highest inputs of riparian (i.e. non-fluvially redistributed) wood recruitment. As such, a large proportion of the wood in those streams spanned the channels, did not get redistributed and did not interact with flow and sediment. Our findings are similar to those of Nakamura and Swanson (1993) in that there appears to be a lower threshold of stream size beyond which wood is unlikely to enter channels and interact with the substrate, despite potentially high levels of wood input from the adjacent forest. In these small streams wood will interact with flow only if it is small enough to be transported in from upstream or breaks upon entry into the channel and can be recruited and redistributed in-situ. Riparian disturbance in these small streams may significantly increase the number of trees toppling into the streams, but is unlikely to result in increased wood function until sufficient time has passed that wood decays and finally enters the channels.

3.4.3 The impacts of riparian wildfire

Generally speaking, the burned streams did not differ widely from the unburned streams in terms of sediment diversity, substrate fining, or the volume of sediment stored in the channels. The volume and diversity of sediment in the channels was largely determined by channel width, although there were some deviations in the burned streams; Deeper Creek stored more sediment volume than would be predicted by its channel width and Bellevue had fewer facies per channel width than would be expected. The functionality of wood in the burned channels, however, did differ in some respects from the unburned streams. Despite Goode and Deeper Creeks being wood-rich in terms of total wood loading, all of the burned streams were considered wood-poor in terms of functional wood, and in general, a lower proportion of wood was functional in the burned streams relative to the wood-rich streams. The low functional wood loadings may be due to increased wood instability post-fire (see Chapter 2). If LWD in the burned streams becomes stable as the watershed recovers and wood accumulates into stable structures, it will likely accumulate and store the majority of the sediment in the channels.

3.5 Summary

LWD plays an important role in determining sediment dynamics in the sediment limited mountain streams of the Okanagan, storing as much as 95% of the total volume of sediment. There was significant variation between the study reaches, with little to no sediment being stored by LWD in the wood-poor channels. Increasing volumes of functional wood were strongly associated with larger volumes of LWD-stored sediment, and the absence of functional wood in channels was associated with limited alluvial development of the streams. Despite elevated levels of recruitment after riparian wildfire, wood inputs from burned forests are currently playing a minimal role in affecting channel morphology, and are generally non-functional. In streams where the majority of the wood spanned the channel rather than interacting directly with flow, wood function was limited and alluvial development of the bed was minimal. Functional wood load was determined to be a better metric of the interaction of wood with sediment in the channels, and we suggest that using total wood load as a predictor of sediment interactions is inadequate. As streams may have high total wood loadings but low functional wood loading and low associated LWD-related sediment storage, studies must make distinguish between total and functional wood loads.

Whereas wood has previously been found to increase sediment diversity in high-sediment supply streams (Buffington and Montgomery, 1999a), our findings indicate that in step-pool systems with large friction factors and limited sediment supply, higher loadings of LWD will not translate directly into higher sediment diversity, nor will they cause sediment fining to the degree seen in high-sediment supply channels. Although LWD may promote habitat diversity through the formation of large channel spanning jams, there can be no assumption in stream restoration projects that adding wood to sediment-limited channels will increase sediment diversity on a reach scale.

Chapter 4: Overall discussion and conclusions

In this study, we utilize five years of repeated wood surveys in small mountain streams of the Okanagan Basin, BC to produce detailed wood budgets that we believe are representative of small streams in the Okanagan and similar landscapes. We use these wood budgets to report on the effects of recent (< 10 year) riparian wildfire and MPB infestation. We identify differences in the wood budget components across a range of streams and provide detailed information on annual patterns of wood recruitment, output and storage in small streams. We use this wood data to identify controls on wood stability in the study streams. Detailed sedimentological surveys of the same streams are used to relate wood stability to wood function and to identify the role of LWD in the sediment dynamics of sediment-supply limited streams, with direct comparisons to previously published data from sediment rich systems.

Wood recruitment in the study streams is dominated by fluvial imports and recruits directly from the riparian forest. Exhumation is an important source of wood in the undisturbed streams, and is likely a contributor to the more advanced decay state of wood recruits in the undisturbed streams relative to either the burned or MPB streams. Output of wood in the channels is through a combination of fluvial export and in-situ decomposition. Burial was not identified in this study. Volumetric decomposition was found to be a significant component of the wood budget despite the limited time span of the study, and should not be considered to be negligible in building wood budgets for other streams.

In the largest stream, wildfire may have promoted bank erosion and associated wood inputs. The fire has significantly increased the volume of wood recruited directly from the hillslopes and the range of sizes of recruited wood in affected streams, and has greatly increased storage of wood in burned streams. The reference streams are at equilibrium with a very slight depletion of wood. The effects of MPB are not yet pronounced in affected streams, although they may be accentuated by the presence of adjacent cutblocks which are common in MPB affected forests due to salvage logging. There is a slight positive accumulation of wood at the MPB affected sites which is expected to increase slowly over the next 30-50 years.

Wood stability in the channels was found to be a function of relative wood size, for which the metric of relative wood sizes defined by Hassan et al. (2005) is a valuable delineation. Furthermore, wood stability was found to significantly increase wood function. In wood-rich channels with stable wood, LWD was found to store as much as 90% of the sediment volume in the channel. The volume of LWD-related sediment storage was found to increase with increasing functional wood density, although it had no relationship to total wood density. The total volume of sediment in the streams was found to be unrelated to either the total or functional wood loading. Wood was found to cause fining of the channel substrate, but did not increase sediment diversity in these sediment limited channels, as has been previously suggested by Buffington and Montgomery (1999a) for high-sediment supply streams. We speculate that in our sediment limited streams, LWD concentrates sediment storage behind large jams, restricting bed mobility and sediment transport. Since sediment supply is low, these LWD-related sediment storage sites are not supplemented by other alluvial storage sites. In sediment rich streams where sediment supply is large enough to maintain additional alluvial storage sites, LWD-related storage translates into higher sediment diversity, but the same is not true for sediment limited streams.

Wood function in both the burned and the MPB streams (which are, by coincidence, also semi-alluvial sites with low functional wood loadings) is limited. However, as wood recruitment and storage increases over the next 30 years, congestion is expected to occur in the channels. Recruitment of large pieces of wood and the formation of jams in the burned streams will likely force sediment storage sites, and wood will take on a primary role in sediment storage. Sediment will likely become more stable and bed load transport will decrease as aggradation occurs primarily upstream of LWD structure. In the MPB streams, significant accumulation of wood will take longer to translate into increased wood function. The alluvial development of these channels is currently limited due to low functional wood loads. Although riparian recruitment levels are expected to increase with time since infestation, wood recruited through mortality will bridge the channel, and not be immediately functional. In time, decay and breakage will increase the loading of wood in the channels and may force the development of an alluvial bed.

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