SPATIAL PATTERNS OF LARGE WOODY DEBRIS IN THE NORTHERN INTERIOR OF BRITISH COLUMBIA

by

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B.A., The University of British Columbia, 2007

A THESIS SUBMITTED IN PARTIAL FULLFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

Master of Science

in

The Faculty of Graduate Studies

(Geography)

THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)

April 2010

ABSTRACT

Large woody debris (LWD) patterns were investigated in 18 streams in the Interior of British Columbia for a variety of stream sizes (1.4-13.7 m bankfull width flow) and forest types (SBS and SBPS BEC Zones). Definition and scaling type for LWD are variable in the published literature. This research reported that both the definition used to define LWD and the scaling technique used to analyze and display LWD affected the results in LWD abundance and volume measures. Although LWD varies by forest type and stream size, the effect of the riparian forest on LWD loading was minimal compared to the effect of stream size for the 18 study sites. Stream characteristics were such as bankfull flow width and depth were identified as predictor variables for LWD abundance and volume. The distribution of LWD was different in wood associated with LWD jams than wood free in the stream. The importance of LWD jams increased relatively with stream size. LWD jams (1) were larger, (2) had an increasingly different distribution of LWD size classes, and (3) had a different distribution of position and orientation classes than free wood with increases in stream size. The patterns observed in the distribution of LWD for orientation and position classes as well as piece size was consistent with the literature: (1) perpendicular wood generally decreased while parallel increased with stream size; (2) bridged wood decreased while wood fully in the bed increased and (3) piece size generally increased with stream size.

Table of Contents

LIST OF TABLES

List of Figures

Acknowledgments

I would like to offer my gratitude to the faculty, staff and my fellow students at UBC, who have inspired me to work and succeed at graduate studies. I would like to thank my committee of advisors who supported me through this process. Dan Hogan and Steve Bird provided time and expertise for both the field research and analysis. I owe special thanks to both Marwan Hassan and Lori Daniels who helped me plan analyses and who both edited my thesis repeatedly. Both of these teachers also supported me through my undergraduate degree and encouraged me on to graduate studies. Without their vital support over the last several years, I would have chosen a different path.

I would also like to thank Eileen Jones, Christie Andrews and Tammy Elliot whom I shared much of my graduate school experience with. These women have been a source of support throughout this experience that was across the hall or an email away.

I have been financially supported by the department of Geography at UBC and NSERC. I was awarded four TA-ships and one scholarship from the department, which allowed me to be financially stable throughout my degree. Additionally I received an NSERC Scholarship during my second year of schooling, allowing me to focus on my research. The research project was also supported by NSERC grant (Hassan) and Canada Forest Services (Hassan and Hogan).

Finally, I would like to thank my family and friends. They have supported me through this experience and helped me finish in a variety of ways. Jeremy Meugens has been especially supportive the last year and a half and I am extremely grateful for his company.

1 INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

Large woody debris (LWD) has been identified as ecologically and geomorphically important at multiple stream sizes. Wood within the channel boundaries can alter flow, regulate sediment storage and transport and increase the diversity of channel habitats (Hassan *et al.* 2005). LWD is defined as downed logs that intersect the bankfull margins of streams (Harmon *et al.* 1986). This thesis explores the spatial patterns of LWD in 18 streams in the Interior of British Columbia.

The abundance and distribution of LWD is controlled by forest characteristics and fluvial processes. The input of LWD is from the riparian forest through both chronic and episodic events (Hassan *et al.* 2005). Chronic inputs of wood are small scale and localized. They reflect an ongoing process such as bank erosion. Episodic events may be spatially or temporally larger and occur much less frequently than chronic events (Bragg 2000). Examples of episodic events that may change LWD loads in the stream are wildfires, landslides, logging and insect infestations (Brag 2000). Once within the stream bank, pieces of wood may be anchored and stable, or could be transported and re-organized within the channel.

LWD research includes studying (1) physical and biologic functioning, (2) spatial and temporal variability, and (3) abundance and volume measures of wood. In spite of that the range of research topics, fundamental gaps exist that make it difficult to compare results across scales or to use the literature as a guide for designing future research. These gaps include:

1. A lack of standard definition for the components of LWD among forest types or stream sizes (Gurnell 2003, Hassan *et al.* 2005).
2. A lack of a standard scaling technique or understanding of the effect of scaling techniques on data interpretation (Hassan *et al.* 2005).
3. A lack of standard terminology for the function and pattern of LWD (e.g. Abbe and Montgomery 2003, Chen *et al.* 2006, Jones and Daniels 2008).

4. A lack of an understanding of the function and pattern in wood abundance and volume across multiple stream sizes (Gurnell *et al.* 2002, Chen *et al.* 2006).
5. A bias in the study site location (Chen *et al.* 2006).

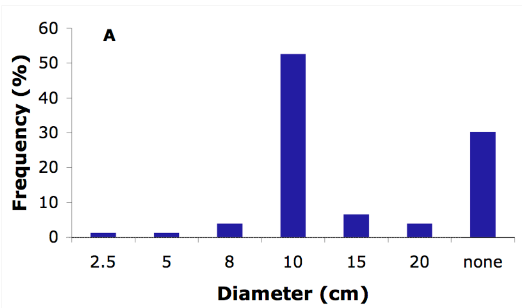
In order to assess the current state of knowledge and on LWD and identify research gaps, a database of 80 papers (heretofore "LWD database") published between 1979 and 2009 was surveyed. All papers within the database were research papers that (1) collected LWD data from field sites or (2) conducted a meta-analysis of multiple previously collected datasets. Originally, the papers were limited to studies in streams <20 m bankfull flow width in order to allow for comparison to the dataset used in this study, however; this restriction was lifted in order to increase the number of papers within the dataset. For this reason, the papers within the dataset may have a bias towards information from streams <20 m bankfull flow width. For each paper, the database contained (1) information about the definition and scaling technique used for LWD analysis, (2) the orientation and position classification scheme, (3) morphologic features including bankfull width and slope, and (4) study site characteristics such as location and disturbance type (Appendix A).

1.2 Multiple definitions

The definition for LWD is inconsistent in the published literature. Ballie and Davies (2002) argued that comparisons across studies in LWD are difficult due to the fact that no "worldwide" definition exists. A worldwide definition could be a single set of size parameters for LWD or a scaled classification scheme incorporating stream characteristics. This section summarizes the current range in size parameters of LWD, the interaction between parameter and stream size, the two suggested ways of defining wood, and site-specific examples of inconsistencies within papers.

1.2.1 Range in size parameters

The dimension for LWD was defined in the methods section of most papers as a diameter and length used to characterize LWD in the field. The most common dimensions used for LWD were 10 cm in diameter and 1 m in length (e.g. Marcus *et al.* 2002, Kreutzweiser *et al.* 2005, Chen *et al.* 2008); however, the diameter and the length used are inconsistent across the literature (Fig 1.1). The diameter ranged from 2.5 to 20 cm with 52% of papers defining the diameter as ≥10 cm. The length ranged from 0.3 to 4 m with 30% of the papers defining the length as ≥1 m. About 25% of the papers did not identify the parameter used for diameter and 42% did not identify the parameter used for length. Generally, the definition of LWD was stated but no explanation was provided for the dimensions used in the study. When a diameter other than ≥10 cm or a length different than ≥1 m or ≥3 m were used, the definition was considered to be abnormal and a brief explanation was provided. An example is the headwater streams which generally used a more inclusive definition such as diameter ≥ 5 cm and length ≥ 50 cm (e.g. Gomi *et al.* 2001). The reason stated was that smaller pieces of wood were functional in headwater streams than would be functional at larger streams.



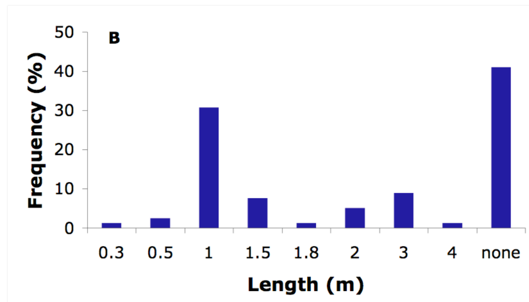


Fig 1.1 Frequency (%) of the diameter and length parameters used in the literature for defining LWD. ≥10 cm and ≥1 m are the most commonly used diameter (A) and length (B).

1.2.2 The interactions between parameter and stream size

The range in diameter and length parameters for LWD in the literature (Fig 1.1) partly reflects variation in the streams that are studied. Streams with bankfull flow width less than 3 m are classified as headwater or small and larger streams are classified as either medium/intermediate or large (e.g. Hassan *et al.* 2005, Chen *et al.* 2008). Church (1992) defined stream size in terms of relative roughness. He argued that large streams are controlled by fluvial processes and geologic constraints, while intermediate streams may be affected by blockages across the channel even though the bankfull flow width is greater than the grain diameter and, lastly, small streams have a larger grain diameter than bankfull flow depth (Church 1992). For the comparison in this literature review, small streams were classified as those with bankfull flow width < 3 m and intermediate/ large streams were classified according to the classification used by the research paper.

The influence of a piece of LWD depends on its size relative to the size of the stream (Hassan *et al.* 2005). A piece of wood that may be considered large at one stream may be small at another. As bankfull width increases, the number of LWD pieces in the stream generally declines (Gurnell 2003, Hassan *et al.* 2005), the mean size of the pieces of wood increases (Abbe and Montgomery 2003, Chen *et al.* 2006), and the volume of wood peaks between 3-5 m bankfull widths (Chen *et al.* 2006).

Martin and Benda (2001) suggest that smaller streams are more likely to have smaller pieces of wood moving shorter distances. Proportionally more of the wood in small streams is larger than bankfull width and, as such, would be less likely to be transported downstream (Martin and Benda 2001). The amount of transportable wood in large streams is greater than in smaller streams, implying only larger pieces of wood can withstand flows and remain in the channel (Martin and Benda 2001). If a more exclusive definition of LWD were applied at all stream sizes, smaller pieces of wood that are functional may be under represented in samples collected from small streams. For example, the definition of LWD used by May and Gresswell (2003) of ≥20 cm in diameter and ≥2 m in length may be considered more exclusive than the ≥10 cm in diameter and ≥1 m in length used by Murphy and Koski (1989).

1.2.3 SUGGESTED WAYS OF DEFINING WOOD

The interactions between stream size and wood function are complex (e.g. Chen *et al. 2006)*. As a result, the effort to produce a standard definition has led to two suggestions:

1. A single set of parameters for all streams in order to standardize across the field.
2. A scaled definition based on site-specific characteristics such as bankfull width and depth (Gurnell 2003, Hassan *et al.* 2005).

The length and diameter parameters in most of the current literature are arbitrary and do not correspond with the function of LWD in streams. Selecting a single set of parameters for LWD definition would eliminate the inconsistency allowing for comparisons across all studies. A single definition for LWD, however, maybe inappropriate over multiple stream sizes as the average size of wood increases with stream size (Chen *et al.* 2006). For example, a piece ≥10 cm in diameter and ≥0.5 m in length in a stream 0.5 m in bankfull width would span the channel and block the flow. In a 20 m wide stream, the same piece would block < 1/40th of the channel width and would have little or no geomorphic effect on the channel. If the same parameters for LWD were used at both stream sizes, one stream may over estimate the number of LWD pieces while not identifying what pieces were functional. These scale-dependent problems highlight the issue that one definition for LWD across all scales will not be appropriate for all streams and research objectives.

In recent reviews, Gurnell *et al.* (2002), Abbe and Montgomery (2003) and Hassan *et al.* (2005) suggested that due to the relation between LWD abundance and stream size, a scaled definition of LWD would be more appropriate than a single set of parameters. A scaled definition would account for the stream morphology and weigh the importance of wood relative to stream size. A piece of wood would be large relative to bankfull width and depth, therefore absolute values could not be compared across sites. This would allow for comparison of the volume or abundance of LWD that is functional as defined by channel characteristics. Gurnell *et al.* (2002), for example, suggest defining the channel size by the wood loading: a small channel is one where the median wood piece length is greater than the bankfull width and the opposite is true for a large channel. Abbe and Montgomery (2003) and Hassan *et al.* (2005) suggest scaling the length and diameter of log by bankfull width and depth, respectively. For example, a piece of wood that is ≥30% of the bankfull width is classified as large (Hassan *et al.* 2005). Positive aspects of scaled definitions are that it would produce a geomorphic basis for defining LWD that relates to wood function and eliminate the use a single definition over multiple scales. Using a scaled definition for all LWD would increase the number of parameters used to define wood, require accurate measurement of channel parameters, and would require the development of a new framework for analysis, making this option difficult to implement. Even with these difficulties, a scaled definition would produce a more accurate description of functional wood at multiple stream sizes and therefore it should be examined as a viable option for defining LWD.

1.2.4 Site-specific examples of inconsistency in defining LWD

Headwater streams are being increasingly studied and can be used as an example to further explore the issues associated with definitions of LWD (Jackson and Sturm 2002, Hassan *et al.* 2005, Gomi *et al.* 2001). Jackson and Sturm (2002) argued for a more inclusive definition for headwaters streams to reflect the fact that the functional size of wood increases with increasing stream width. There is no consensus in the literature about what constitutes a 'more inclusive' definition. Gomi *et al.* (2001) used 10 cm in diameter and 0.5 m in length, Jackson and Sturm (2002) used 10 cm in diameter and 1 m in length, and May and Gresswell (2003) used 20 cm in diameter and 2 m in length to define LWD. Even though all three had study sites in the Pacific Northwest, the difference in definition makes it difficult to compare their results.

In a few instances the definition of LWD changed within a single published paper. Murphy and Koski (1989) defined LWD in the introduction of their paper as ≥10 cm in diameter and ≥1 m in length. This paper is cited repeatedly as being the standard for the dimensions associated with LWD. On a close read of the methods section, however; Murphy and Koski (1989) note that in spite of their definition stated previously, only wood ≥10 cm in diameter and ≥3 m in length would be used in the analysis. No reason was given for this shift in the parameters of the definition. Martin and Benda (2001) calculated LWD budgets for 28 streams in a single catchment in Alaska, depending on stream size they used two definitions for LWD length. For streams with bankfull width <5 m the length parameter for LWD was ≥1.5 m, but for steams with bankfull width ≥5 m LWD length was ≥3 m. For the analysis, all of the streams were grouped together and compared. The relative abundance of LWD was plotted against drainage area and classified into LWD length groups. When comparing the relative abundance of LWD to multiple LWD length groups, Martin and Benda (2001) divided the results into four stream-width classes. The results indicated that streams that were 3-5 m wide contain 20% of the wood in the 1.5 m length class, with none of the other stream-size categories having any wood in a category less than 3 m. This interpretation is misleading as it suggests no LWD that was <3 m in length existed in streams ≥5 m wide, when in fact this size class was not measured. This misinterpretation is a reflection of the multiple definitions used at the different stream sizes.

1.3 Scaling and data presentation

Scaling data to a common spatial unit is necessary for comparing the abundance and the volume of wood measured at multiple sites. In research on LWD, scaling is applied inconsistently and no work has assessed the effect of different scaling techniques on LWD abundance and volume.

1.3.1 Inconsistency in the field of LWD

In LWD studies, a variety of scaling techniques have been used to analyze and present and data (Fig 1.2). About 70% of the surveyed studies in the LWD database reported a scaled measure of LWD abundance while 30% did not scale the data. Out of 80 surveyed papers, 39% used reach length as a scaling tool (e.g. Petit *et al.* 2006), while an additional 12% used reach length and area or the product of both (Warren *et al*. 2008). The most common reach length was 100 m long, though 50 m and one kilometre lengths were also applied. Scaling by length allows comparison of LWD abundance among reaches of different length but it does not take into account other important morphologic elements such as bankfull width and bankfull depth, which strongly affect stream geomorphology. Scaling by area was the second most common technique and accounts for geomorphic features of the stream by including the bankfull width when calculating the scaled unit. This technique was used as the only scaling technique in 20% of the surveyed papers (e.g. Lienkaemper and Swanson 1987) and as a secondary technique with length in 10% of the papers. Scaling by unit area was the most common unit, but scaling by 100 m^2, bankfull width squared, and hectare were also used. The remaining techniques include scaling by width and time (e.g. number of pieces recruited per year in Downs and Simon 2001).

There is no consensus on the best or most appropriate scaling technique (Fig 1.2). For consensus and to facilitate comparison across studies, the least biased scaling technique should be determined and then used throughout the field. The least biased scaling technique would meet the following criteria: (1) accounts for the most physical variables to build the most standardized unit for comparison and (2) reduces the differences due to definition parameters used in the field.

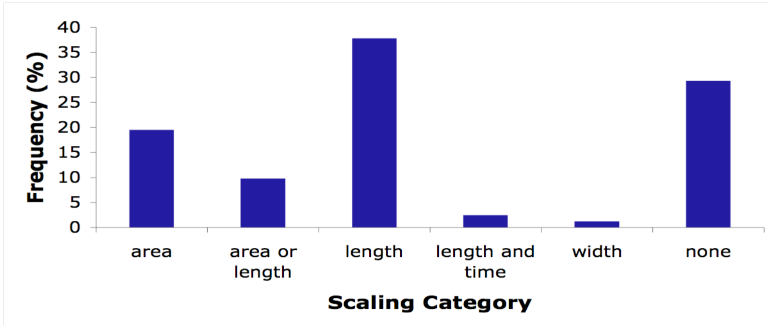


Fig 1.2 Relative Frequency of scaling techniques recorded in the 80-paper database

1.3.2 Comparison of scaling techniques, hypothetic and concrete examples

A comparison of the two most common scaling techniques using a hypothetical example demonstrates how scaling can effect interpretation of LWD abundance (Table 2.1). Site A and B used the same length of survey reach and measured the same abundance of LWD. The only difference between the two sites was the bankfull width, which increased from site A to site B. If reach length were used to scale LWD frequency, the sites would be considered equal in terms of abundance (Table 2.1). If bankfull area were used to scale wood, there would be a decrease in the number of pieces from 0.5 pieces/m^2 for site A to 0.1 pieces/m^2 for site B. This example has illustrated that the two scaling techniques produce two different results and data interpretation. Scaling by length suggests that wood abundance does not decrease with increasing stream size while scaling by area produced a decreasing pattern with increasing stream size. Furthermore, scaling by area produces a scaled unit that accounts for geomorphic variables and provides standardized unit for comparison across sites.

Robison and Beschta (1990) measured LWD volume and abundance in 5 channels in Southeast Alaska. They reported volume as both a function of reach length and area: (1) volume increased with stream size when scaling by length and (2) decreased with stream size when scaling by area. The abundance measure was only reported as a function of length and was reported to decrease with increase in length. When I recalculated the values as a function of area, the LWD abundance decreased with increased stream size. For these streams, the different scaling types have a direct impact on the pattern in LWD and, therefore, concretely show that a common scaling technique is required to standardize research of LWD.

Table 1.1 Hypothetic example for comparison of two scaling techniques

Site	Bankfull width (m)	Survey length (m)	Survey area (m^2)	# Pieces measured	Pieces/length (#/100 m)	Pieces/area (#/m^2)
A	2	100	200	100	100	0.5
B	10	100	1000	100	100	0.1

1.4 LWD DISTRIBUTION AND FUNCTION

Poole (2002) argues that the links between multiple scales and complex patterns in the fluvial landscape must be studied to understand the function and preservation of the fluvial system. Across field studies however, there is no consistent or common language applied to LWD when measuring and describing the function of wood. Additionally, there are few comparisons between jammed and free wood and wood across multiple stream sizes. It is difficult to explore complex patterns and have a coherent understanding of the function of LWD in fluvial systems when terminology within the field is not consistent. The remainder of this section will summarize the literature on (1) the effects of jams, (2) the controls on the function of LWD, and (3) patterns over multiple stream sizes in order to understand how the current research attempts to understand the complex links between LWD and the fluvial system.

1.4.1 JAMS

For the purpose of this study, LWD jams are defined as two or more pieces of interacting wood (Hogan 1987). LWD jams produce important geomorphic units that regulate bed material, sediment transport, and influence the morphology upstream and downstream (Church 1992, Hachenburger and Rice 1998). Log jams form and break apart over time and, as such, their influence on stream channels change with time (Hogan *et al.* 1998). Most of the research on LWD jams has been conducted in the Pacific Northwest (PNW) region of North America with a few papers from the east coast of the United States and Australia.

Research on LWD jams generally focuses on (1) morphology of the log jam, (2) the spacing between jams, and (3) the effect of individual jams as a unit instead of a collection of separate pieces (e.g. Haschenburger and Rice 1998). Abbe and Montgomery (2003) measured the distribution of wood in jams and found a difference in the functional size of different pieces of wood within a jam. They argue that key pieces in jams were generally larger than either the bankfull width or the bankfull depth and they were generally the largest pieces in the jam. Free wood is defined as wood not associated with a jam. Similarly, orientation, position and functional size of free wood versus jammed wood have not been compared.

1.4.2 CONTROLS ON LWD FUNCTION

LWD function is controlled by size, position, orientation and decay class (Chen *et al.* 2008; Jones and Daniels 2008). LWD size is measured as diameter and length. The size of individual pieces of wood relative to channel parameters dictate geomorphic importance and are used to determine the critical size of functional wood in a stream (e.g. Hassan *et al.* 2005). As a result, the definitions of LWD in the literature are inconsistent among streams of different sizes and the effect of variation in the definition on comparative analyses is poorly understood. Position can be identified two ways: (1) the vertical distribution of wood in the steam or (2) as wood located within a LWD jam or free in the stream. Orientation is a measure of the angle of a piece of wood relative to the streambed (e.g. Hassan and Hogan 2007; Jones and Daniels 2008). The decay class of individual pieces of wood is sometimes recorded, however; this component is not as prominent or as well defined as the other components of function. The interactions among position, orientation and decay at single or multiple stream sizes were not reported in the literature reviewed for this chapter.

In the surveyed literature on LWD, 51% of papers had a categorical classification for position of wood. Position was generally divided into multiple classes that could be classified into two broad categories: (1) wood outside the active channel and (2) wood within the channel or streambed. Robison and Beshta (1990) defined two zones vertically within the bankfull width flow channel and two zones outsize of the channel surface, while Chen *et al.* (2008) had four categories including 2 zones within the bankfull width flow, one bridged over or fully out and a final zone as a combination of the other three. Jones and Daniels (2008) also identified four zones: (1) bridge, (2) partial bridge, (3) loose, and (4) buried. Most classification schemes were worded slightly differently, but all differentiated between wood interacting with the bank margins and wood outside bankfull width. This distinction is probably because position indicates the likelihood of a piece of wood interacting with stream flow. When comparing the function of different positions using equivalent sized pieces, for example, a piece in the bed would be more functional than a bridged piece. The piece in the bed will modify flow regime, store sediment and might cause bank erosion. Additionally LWD that is half in the bed or bridged is more stable and less likely to be transported downstream than wood in the bed, suggesting that distinguishing wood interacting with the flow may indicate the mobility of wood (Martin and Benda 2003). Generally, the amount of bridged wood decreased with increases in stream size, while the amount of wood fully in the stream increased (e.g. Chen *et al*. 2006).

Orientation measurements were reported in 50% of surveyed papers. The orientation of wood was generally divided into four categories (e.g. Richmond and Fausch 1995, Chen *et al.* 2008): (1) perpendicular to stream flow; (2) diagonal with apex of the log oriented upstream; (3) diagonal with apex of the log oriented downstream and (4) parallel to stream flow. Each orientation class interacts with stream flow differently. For example, wood perpendicular to the stream would be more functional than wood of the same size parallel to the streambed. This is because a perpendicular piece would interact more with the stream flow. Orientation has been reported as (1) the angle at which wood falls into the stream from the riparian forest and (2) the angle of LWD relative to stream flow, whether it has been re-organized by flow or has not moved since entering the stream. Sobota *et al.* (2006) reported no difference in the directionality of tree fall between different species when developing a wood recruitment model; however, they did report LWD to fall directly towards (perpendicular) the stream at 16 sites and in an upstream direction (diagonal upstream) at four sites. Gurnell *et al.* (2002) reported that in a multi-scale study that measured more detailed orientation classes, perpendicular wood decreased with stream size, while wood parallel to the bed increased. Chen *et al.* (2008) reported similar changes in orientation with stream size. Orientation could be measured in a very detailed manner, however; studies that have reported more specific degree values (0-360), tended to clump values in a similar pattern to the four categories of perpendicular, upstream, downstream and parallel (e.g. Gurnell *et al.* 2002).

Size is the third major control on the function of a piece of wood in a stream. The mean size of wood increases with stream size (Mossop and Bradford 2004, Chen *et al.* 2006). Ideally, the parameters used for length and diameter of LWD would include all functional wood within the study reach and minimize the redundancy by measuring wood too small to be functional. Being able to identify a 'threshold' size would improve the efficiency of fieldwork as only the functional wood would be measured, instead of all wood of an arbitrary size, regardless of function. Most surveyed papers did not state a functional size; instead, size parameters for LWD were absolute and function was implied by the absolute or relative amount of wood found in different positions and orientations (e.g, Gomi *et al.* 2001). Abbe and Montgomery (2003) studied the stability thresholds of logs in jams and defined three position categories: key, racked and loose. They produced a dimensionless plot to look at the size of wood in relation to orientation. They showed a clear grouping of data into functional sizes; key pieces were generally larger, the most stable and had the highest function within the jam. Chen *et al.* (2006) and Chen *et al.* (2008) explicitly state the mean length and diameter of wood at multiple stream sizes as well as the percentage of functional and non-functional LWD volume and pieces. Although all studies will have slightly different goals and focuses, identifying a common language, display and measurement for size of LWD will allow for stronger comparisons across research.

A fourth component of function of LWD is the decay class. It is difficult to determine how long wood has been in a stream or how old the wood was when it entered the stream (Hyatt and Naiman 2001). Adding to complexity is the fact that decay rates depends on species and climate (Morrison and Raphael 1993, Gurnell 2002). Hyatt and Naiman (2001) used dendrochronology and ^{14}C dating and reported residence times of wood from one to 1400 years, with > 80% of the pieces being < 50 years old in streams in the Queets River, Washington. Hyatt and Naiman (2001), however, found no linkage between age and decay class when a seven-point decay class was applied. The main decay class difference was between conifers, which were much more represented in the stream than hardwoods such as red alder, which were abundant in the riparian forest. Decay classes representing physical stages of log decomposition are more commonly used in LWD studies than labour-intensive dendrochronology techniques. Martin and Benda (2001), Jones and Daniels (2008), and Chen *et al.* (2006) each used decay classification, however; each study used a different scheme with number of decay classes ranging from three to seven. The use of multiple decay classifications makes comparisons across studies more difficult as the class definitions must be compared and may not be cohesive.

1.4.3 Multi-Scale studies

Stream size and channel morphology change with drainage area (Church 1992, Montgomery and Buffington 1998, Gurnell *et al.* 2002). The processes that drive and form a headwater stream are different to those in medium and large streams (Gomi *et al.* 2001, Gurnell *et al.* 2002, May and Gresswell 2003, Hassan *et al.* 2005). Therefore, it is a reasonable hypothesis that abundance and function of wood change with stream size.

In the LWD database, most studies were conducted on streams of one size, usually a medium sized stream, and characterized the wood within that stream. If wood functions differently in different stream sizes, then more research should be done in small and large streams to balance the volume of research in medium streams. LWD in headwaters streams have been identified as functioning differently than LWD in larger streams (e.g. Gomi *et al.* 2001). This suggests that more research is needed at a variety of stream sizes in order to understand how wood functions throughout a watershed. Within the surveyed papers, 33% reported study sites in streams with bankfull width <3 m. Of the 33% of papers that included small streams, 50% were included as part of a multi-scale studies that were conducted on streams of a range of sizes.

1.5 Study Site

1.5.1 Location

In the LWD database, 51% of the papers reported on study locations in the PNW (e.g. Ward and Aumen 1986), 20% in midwestern (e.g. Young 1994) and eastern (e.g. Bilby 1984) North America, 12% in Europe (e.g. Piegay *et al.* 1998), 11% in the southern hemisphere (e.g. Webb and Erskine 2003) and 6% in montane and boreal North America (e.g. Kreutzweiser *et al.* 2005).

Research on LWD has been highly concentrated in the PNW, which may cause a bias in the current knowledge and understanding of LWD. Studies worldwide have measured much lower values in wood abundance and volume than the PNW. The PNW has higher volumes of wood due to riparian zone composition related to the BEC zone, piece size, recruitment rates and mechanisms, and decay rates (Ballie and Davies 2002 Hassan *et al*. 2005). Chen *et al.* (2006) suggested LWD volumes from the southern interior of BC were low compared to those in the PNW, but were similar to those in the boreal forests growing on the Canadian Shield. Mossop and Bradford (2004) also compared regional values and found that streams in the boreal forest had significantly lower volumes and frequency of LWD than the PNW. Work by Comiti *et al.* (2006) also suggests LWD volume and frequency from the PNW are higher than those measured in the Italian Alps. If the abundance and volume is different, than the function or the distribution of orientation and position size classes may also be different.

Direct comparisons of the abundance of LWD in streams has proven difficult because of the tremendous variety of riparian forests and stream sizes within and between regions and at a global scale. To address this problem Gurnell (2003) grouped study locations into 4 general forest types to compare LWD volumes and reported that: redwoods > other conifers> mixed conifers and hardwoods> Salicaceae. Gurnell (2003) argued that these findings indicate that forest type is an important consideration for analysis and meta-analysis of LWD data.

1.5.2 DISTURBANCE

Disturbance of riparian forests has a dominant influence on LWD structural patterns (Bragg 2000). Bragg (2000) modeled multiple disturbance types, ranging from episodic, catastrophic disturbances to chronic, individualistic tree deaths, and determined that they influenced the riparian forest composition and LWD in terms of amount of wood available for recruitment, the storage of wood and the timing of recruitment. Bragg (2000) urged further research on what he termed ‘catastrophic disturbances’. He suggested that natural large disturbances function very differently than human produced disturbances and as such research needs to be done, especially if logging is supposed to mimic natural disturbance. This may be especially pertinent in BC due to the outbreak of mountain pine beetle (MBP). Hassan and Hogan (2007) calculated wood budgets for

18 streams in the interior of BC and found that MPB has little to no effect on the budgets because of the fact that lodgepole pine (*Pinus contorta* ssp*. latifolia*) is not generally a riparian species.

LWD studies include sites with a variety of natural and human disturbances. Within the LWD database, 45% of the literature included study sites in old growth or natural forests with no disturbance (e.g. Diefenderfer and Montgomery 2009), 28% reported only the effect of logging (e.g. Cordova *et al.* 2007), while 5% reported logging and a secondary disturbance such as fire or windthrow (e.g. Andrus *et al.* 1988). An additional 6% reported the effect of fire (e.g. Zelt and Wohl 2004), while 1.2 % looked at a variety of disturbances including, insect outbreaks (Hassan and Hogan 2007), windthrow (Martin and Benda 2001), debris flows (Gomi *et al.* 2001), ice storms (Kraft and Warren 2003) and flooding (Wyzga and Zawiwjska 2005) and 3% of the papers were about flume experiments. In some studies, disturbance was reported to have produced a 'clean slate' which allowed the authors to study how wood was recruited and reorganized within a stream. In other cases, understanding the effect of the disturbance itself was the entire focus of the study. More information is needed on some of the less represented disturbances in order to understand the complex linkages between LWD patterns and disturbance.

1.6 Gaps in knowledge and Thesis Objectives

This literature review has identified several key gaps in knowledge at both the global and the local scale. At the global scale, there is (1) no consistent definition or understanding of the affects of multiple definitions of LWD and (2) no consistent scaling technique or way to present data. These gaps make it difficult to (1) explore patterns at multiple stream sizes or field sites, (2) compare studies to published literature and (3) produce meta-analysis using the published literature and the vast database of LWD that has already been collected. At the local scale, research in BC has been focused in coastal forests. Results from this study provide valuable information on the LWD from the Interior of BC.

The two main goals of this study were (1) to understand the impact of multiple LWD definitions and improve comparisons across studies and (2) to understand the patterns and controls on LWD across multiple stream sizes. In order to meet these goals, this thesis had several specific objectives:

1. To identify appropriate parameters for the definition of LWD.
2. To identify the least biased way to present data across multiple stream sizes.
3. To identify the most important influences on the input and reorganization of LWD at multiple stream sizes.
4. To identify the most important control on the function of LWD. The function of LWD was defined as a combination of position, orientation and LWD size.
5. To identify the effects of jammed wood and the characteristics of LWD at multiple stream sizes

1.7 Thesis Outline

Chapter 2 introduces general and specific study site characteristics as well as the field methods and variables derived from the field data. Variables included (1) volume and abundance of wood, (2) stream characteristics from longitudinal profiles and (3) riparian forest indices and importance values. Chapter 3 explores the effect of multiple definitions on LWD data collected and analysis. Chapter 4 explores the controls on LWD input and reorganization. This chapter assesses the impact of riparian zone and stream characteristics in order to understand controls on LWD distribution. Chapter 5 addresses the controls on the function of LWD. The patterns in LWD were explored while accounting for size, orientation and position. Chapter 6 is the study conclusions.

2 Study Sites, Field Methods and Minor Data Analysis

2.1 Overview of the study design

The study was designed and conducted by Hassan and Hogan (2007). This chapter will provide a summary of the study sites and field methods, which is based on Hassan and Hogan (2007). This study reports on 18 study sites in the interior of BC, nine sites each in the Sub Boreal Spruce (SBS) and Sub Boreal Pine Spruce (SBPS) biogeoclimatic zones (Appendix B). Six of the sites had been previously surveyed in 1998 and 1999 and the 12 new sites were selected based on proximity to the previous sites in order to assess the spatial variability of the channel conditions and riparian zones. The study was designed to represent a variety of stream sizes as well as two forest types. Hassan and Hogan (2007) identified six ‘morphometric regions’ based on biologic and physical characteristics and sampled three sites within each region. The general characteristics of each study site will be discussed in terms of the morphometric region with which it was associated.

2.2 General watershed characteristics

Physical attributes of the sites were variable to represent the range of conditions in the broader study region across the eighteen study sites. Hassan and Hogan (2007) grouped the 18 study sites into six morphometric regions, based on the biophysical characteristics of each watershed (Table 2.1). Table 2.1 identifies the major physiographic zone, hydrologic zone, vegetation cover, drainage class, soil type, geology and BEC zone for each morphometric region and the study sites associated with each region (Hassan and Hogan 2007). Several of the regions had large overlaps in the biologic and physical characteristics and as such the field sites had a large overlap in characteristics. The remainder of this section will define the characteristics of the physiographic, hydrologic and BEC zones associated with the study sites as well as the drainage class, soil type and geology.

The physiographic zones were divided into the Interior Plateau and the Northern and Central Plateaus and Mountains (Table 2.1). The Interior Plateau is located in the rain shadow of the Coast Mountains, has a large range in annual temperatures and the precipitation is distributed throughout the year (Shaefer 1978). The Northern and Central Plateaus and Mountains are characterized by long, cold winters and short cool summers, with precipitation distributed throughout the year (Shaefer 1978).

General rock-types influence rates of erosion, sediment production and slope stability (Hassan *et al.* 2008). The three primary geologies associated with the study sites were volcanic, sedimentary and intrusive. The soil types were classified as dystric brunisols and humo-ferric podzols (Table 2.1). Podzols are well-developed soils usually located in well-drained coarse textured material and are strongly acidic (Valentine *et al. 1978*). Podzols are typically found under coniferous forests. Brunisols are acidic soils that are poorly developed. They typically develop under forests and are seen as an intermediate step in soil development, even though brunisols can persist for long periods of time. BC is divided into ten hydrologic zones with similar hydroclimatic regions. The 18 sites were located in either the Chilcotin/Cariboo Plateau or the Northern Interior Region (Table 2.1). Both zones have a continental climate with the Northern Interior region being drier and cooler than the Chilcotin/Cariboo Plateau region.

The forest types were identified as Sub Boreal Pine Spruce (SBPS) and Sub Boreal Spruce (SBS) based on the division of BC into 14 biogeoclimatic (BEC) zones. The SBPS zone is generally a drier zone than SBS, but has similar winter temperatures and cooler summer temperatures (Steen and Demarchi 1979). The subzones associated with the SBPS, SBS, SBPS sites were very dry and cold (xc), wet cool (wk) and moist cold (mc), respectively. The soils associated with SBPS zone are generally poor and Brunisols are common, as was the case with the nine field sites in this biogeoclimatic zone. The vegetation cover was classified as 1.0 for all sites, which means that there was 100% vegetation coverage and no logging within the boundaries of the studied watersheds.

,

Table 2.1 The general biophysical characteristics of the six morphometric regions. This table was adapted from Hassan *and Hogan* (2007).

<table>
<tr><th>Morphometric Region</th><th>Study Sites</th><th>Physiographic Zone</th><th>Hydrologic Zone</th><th>Vegetation Cover</th><th>Drainage Class</th><th>Soil Type</th><th>Geology</th><th>BEC* zone and subzone</th></tr>
<tr><td>Hotnarko</td><td>Hotnarko
Kappan 5
Kappan 5</td><td rowspan="4">Interior Plateau</td><td rowspan="3">Chilcotin/ Cariboo Plateau</td><td rowspan="6">1.0</td><td rowspan="3">Rapid to well drained</td><td rowspan="3">Dystric Brunisol (mesisol)</td><td>Volcanic (Alluvium or till)</td><td rowspan="3">SBPSxc</td></tr>
<tr><td>Precipice</td><td>Precipice
Nimpo
Kappan 3</td><td rowspan="2">Volcanic (Intrusive)</td></tr>
<tr><td>Kappan</td><td>Kappan 1
Kappan 2
Natsidalia</td></tr>
<tr><td>Thautil</td><td>Thautil 1
Thautil 2
Thautil 3</td><td rowspan="3">Northern Interior</td><td rowspan="3">Well drained</td><td rowspan="3">Hummo-Ferric Podzolic</td><td>Volcanic (Sedimentary)</td><td>SBSmc</td></tr>
<tr><td>O’Ne-el</td><td>O’Ne-el
Bivoac
Sidney</td><td rowspan="2">Northern and Central Plateaus and Mountains</td><td>Sedimentary (Intrusive)</td><td rowspan="2">SBSwk</td></tr>
<tr><td>Forfar</td><td>Forfar
Gluskie
Van decar</td><td>Intrusive (Sedimentary)</td></tr>
</table>

2.3 DATA COLLECTION

Data were collected during July and August of 2006. Stream morphologic, riparian forest and large woody debris (LWD) data were collected in order to understand the input mechanisms of wood to the stream as well as the function and patterns of LWD within the channel. In the field, the specific location of each study site was determined:
1. For previously surveyed sites, by the location of the surveys during the 1998/1999 field season based on benchmarks left in the field
2. For new sites, by the location of a reach that was composed of riffle-pool units and that had no drastic changes in slope or morphology over a short distance of stream. This selection criteria was used to make the sites homogonous and to allow for comparison across multiple sites.

2.3.1 STREAM MORPHOLOGY

To determine the morphologic units within each study site a longitudinal survey was conducted. Survey equipment included an automatic level survey, stadia rod and a hip chain to record distance and elevation changes along the thalweg. The length of the survey varied by site and depended on the bankfull width. The surveyed lengths at each site were 50 times the bankfull width. The interval of one bankfull width was used for measuring the elevation of the thalweg, water surface, bars and banks. Additional survey points were included when a change in morphologic feature occurred between the intervals of one bankfull width. At every fifth bankfull width a valley cross section was sketched with distances measured using a meter tape. The D_{95} (the 95% of the particle size distribution) was visually estimated at each bankfull width at the same place the elevation and distance were recorded.

2.3.2 RIPARIAN FOREST

Four plots were located in the riparian forest and measured at each study site. The plots alternated between the left and right banks of the streams and were distributed approximately 10 bankfull widths apart. Each plot was a circle with a radius of 3.99 m and area of 50 m^2. All trees within each plot were measured. Categorical data recorded for each tree included the species and mortality. Mortality had two levels which were defined as 'living' or 'dead', which was assessed visually. The diameter at breast height (DBH) was measured using a DBH tape at 1.3 m. For trees <1.2 m in height, a meter tape was used to measure the height of the tree directly. For trees >1.2 m in height, a clinometer and measuring tape were used for the calculation of tree height (Fig 2.1).

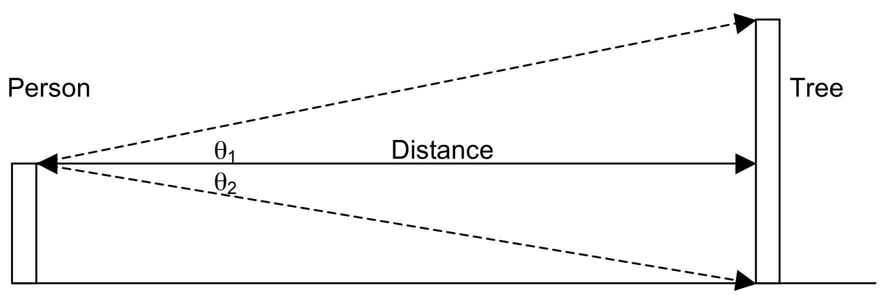


Fig 2.1 Diagram of the procedure used to measure the height of trees. The angles θ_1 and θ_2 represent the angles measured using the clinometer.

2.3.3 LWD

The total LWD load was estimated for each study site using an ordered category system adapted from Hogan (1989) to estimate wood size parameters and function based on class characteristics. At each bankfull width the total wood load was estimated as the wood halfway between the surveyed bankfull width upstream and the bankfull width downstream. The remainder of this section will describe the estimates of wood size and the class system used to infer function of the wood. To minimize subjectivity all wood surveys were conducted by the same researcher.

Table 2.2 outlines the categorical division used in the field for estimating the diameter, length and abundance of pieces. Individual logs were not measured and instead the categories were used to produce a visual estimate of the LWD. This system was used to reduce the amount of fieldwork due to the long reach surveys, which in some cases included hundreds of metres of channel length. Using the categorical inventory allowed rapid data collection over long reaches and better representation of in-channel wood characteristics.

Three position classes were recorded and represent the vertical distribution of wood in the stream. These positions are bridged, half in the bed, and fully in the bed. Bridged wood was a piece of wood suspended over the stream and not functional due to minimal interaction with the streambed. Half in the bed was a piece of wood half in the streambed that may have been anchored to the bank and had moderate interaction with the streambed and flow. Wood fully in the bed had high levels of interaction with the streambed and water flow as this category was used for pieces of wood contained fully in the streambed. In terms of orientation, three classes were recorded representing the potential blockage of wood across the bankfull width. These classes included parallel, diagonal upstream and perpendicular. Wood parallel to the stream had low potential water flow blockage as it was streamlined. Wood diagonal potentially blocked more of the water flow and diverted water producing different pool types. Wood perpendicular to the streambed potentially blocked the most water flow and was classified as high interaction with flow.

Wood was grouped in the field into a jam class. The two levels of this class included (1) wood free in the stream and (2) wood located in a jam. Jammed wood was defined as the interaction of two or more pieces of wood (Hogan 1989).

Table 2.2 The categorical divisions used in the field for estimating diameter, length and abundance. This system was modified from Hogan (1989).

Rank	Diameter (m)	Length (m)	Abundance (#)
<1	<0.05	<1	N/A
1	0.05-0.1	1-5	<2
2	0.1-0.3	5-10	2-3
3	0.3-0.7	10-15	4-7
4	0.7-1.2	15-20	7-12
5	>1.2	>20	>12

2.4 DATA ORGANIZATION AND BASIC CALCULATIONS OF FIELD DATA

Excel Version 11.5.0 and SAS version 9.1 were used for database management and analysis. The majority of calculations, statistical work and analysis were conducted in SAS 9.1 with some minor work being done with Excel 11.5.0.

2.4.1 STREAM MORPHOLOGY

The longitudinal profile was used to calculate bankfull depth and reach average slope. The average bankfull width was calculated using measurements extracted from the valley cross sections. Additionally, the longitudinal profile was used to calculate absolute and relative length of the thalweg and the change in elevation associated with each type of morphologic unit surveyed in the stream.

2.4.2 RIPARIAN FOREST

Tree heights and volumes, biodiversity indexes and importance values for each of the species within each site were calculated in order to characterize the riparian zone composition. Tree height (h) was calculated for all trees >1.2m as

$$h=d*\tan(\text{radians}(\theta_1))-d*\tan(\text{radians}(\theta_2) \quad [1]$$

where d is the measured distance and θ_1 and θ_2 the angles (see Figure 2.1) .

Assuming a cone, the volume of each tree ($Tree_{volume}$) was calculated as

$$Tree_{volume}=1/3\pi r^2 h \quad [2]$$

Where r is the three radius.

Three biodiversity indexes were calculated for each plot and averaged for each site (Barbour *et al.* 1999). The first is the Simpson's Indices for diversity (C -- eq. 3), the second is the dominance (D -- eq. 4) and the third Shannon-Weiner Index (H'-- eq. 5)

$$C=\Sigma(pi)^2 \quad [3]$$

$$D=1-C \quad [4]$$

$$H'=\Sigma(pi)(\ln pi) \quad [5]$$

where, *C* represents dominance; *pi* is the proportion of all individuals in the sample that belong to species *i; D* represents diversity and is derived from dominance (*C*). The Shannon-Weiner Index was calculated to understand the uncertainty of the community (Barbour *et al*. 1999).

Importance values were calculated by combining species-specific data from four plots measured at each site. Importance values are defined as the sum of the relative basal area, relative density and relative frequency of each species (Barbour *et al.* 1999). The importance value for any species in a community ranges from 0-300 (Barbour *et al.* 1999). The relative basal area, density and frequency for each species were calculated based on species basal area, frequency and density. The basal area (eq. 6) for each tree is

$$BA=\pi(DBH/2)^2 \quad [6]$$

where, BA is basal area and DBH is the diameter measured at breast height for each tree. Species basal area was calculated as the total basal area for a single species divided by the total basal area of the inventoried plots within each site. The species density was calculated by dividing the total number of stems tallied for a single species divided by the area of the inventoried plots within each site. To obtain species frequency we divided the number of plots in which the species were tallied by the total number of plots at each site. The relative basal area, density and frequency for each species were determined by dividing the species basal area, density, or frequency by the total species basal area, density or frequency.

2.4.3 LWD

Values associated with each of the categories were applied to each row of data based on the categorical number received in the field for abundance, length and diameter (Table 2.3). Each row of the data was associated with an individual length, diameter, and abundance value and a position, orientation and jam class. For each row, the length and diameter values were used to calculate the volume of the piece associated with that individual row assuming the shape of a cylinder (eq. 7).

$$Volume_{Log}=\pi r^2 l \qquad [7]$$

The total volume ($Volume_{Row}$) for the row entry was calculated by multiplying the volume of the log size by the estimated abundance (A_{est}) of wood associated with that row (eq. 8).

$$Volume_{Row}= A_{est} * Volume_{Log} \qquad [8]$$

For the majority of the LWD analysis, the total abundance for each row was scaled by the area of the stream surveyed (eq. 9).

$$Area=Survey_{length} * Width_{bf} \qquad [9]$$

The total volume of each row was scaled by the volume of the stream surveyed. The stream volume is equal to: (eq. 10)

$$Volume= Survey_{length} * Width_{bf} *depth_{bf} \qquad [10]$$

Summary tables were calculated for both abundance and volume measures using multiple combinations of the class variables of position, orientation and jam that were recorded in the field (Sample: Appendix E). These calculations and involved identifying specific class combinations for which the program identified the total volume and abundance of LWD associated with the identified class combinations at each site. The sites in these tables were then classified by stream size and forest type.

Table 2.3 The values associated with the field categories for diameter, length and abundance.

Rank	Diameter (m)	Length (m)	Abundance (#)
<1	0.05	0.5	N/A
1	0.1	3.0	2
2	0.2	7.5	2.5
3	0.55	12.5	5
4	1.0	17.5	10
5	1.5	20	15

3 THE EFFECT OF DEFINITION AND SCALING ON THE STUDY OF LWD

3.1 INTRODUCTION

Consistent definition and scaling are a major limitation on the understanding of wood dynamics in streams. The parameters used to define LWD length and diameter vary, as does the scaling type used to present and analyze LWD abundance and volume data. Therefore, this chapter explores how definition and data presentation affects the values measured and patterns observed in LWD. Without a basic understanding of the effect of the variations in the parameters used to define and unit used to scale LWD, an objective standardization and comparison across the field is not possible. Progress on the topic is hampered by the lack of standardized guidelines, definitions, measurements, and scaling techniques.

The specific questions that guided the research in this chapter are:

1. Is there an acceptable set of parameters to define LWD in the literature?
2. Does the variety of definitions in the literature affect the results?
    a. Are the values measured and patterns observed in LWD affected by the parameters of the definition used for LWD?
3. Is there a standard way that LWD should be presented for analysis?
    a. Can the effect of the parameters of the definition used for LWD be minimized in analysis through scaling techniques and data presentation?

These questions are fundamental for progress in the field of wood dynamics in streams. Both Gurnell (2003) and Hassan *et al.* (2005) argued that the variety of definitions in the field make it difficult to make comparisons across studies.

3.1.1 DEFINITION OF LWD

The parameters used to define LWD were inconsistent in the literature. LWD is defined as a measure of the length and diameter parameters, however; these measurements changed with stream size or study region. The components of the definition of LWD range in the literature from 2.5-20 cm in diameter and 0.3-4 m in length (e.g. Bilby 1984, Piegay *et al*. 1998, May and Gresswell 2003, and Comiti *et al.* 2006). Smaller streams with bankfull width < 3 m often had a more inclusive definition, meaning that a smaller piece of wood was classified as LWD in smaller streams (e.g. Gomi *et al*. 2001). Streams located in the Pacific Northwest (PNW) used more exclusive definitions than streams in the Boreal Forest. The forest type was usually cited as the reason for being able to use a more exclusive definition in the PNW and still measure the functional wood (e.g. Hassan *et al.,* 2005; Kreutzweiser *et al.* 2005). The most common definition combination was 0.1 m in diameter and 1.0 m in length, however, multiple combinations are common and few definitions had explanations (e.g. Murphy and Koski 1989). This inconsistency in the literature makes it difficult to choose an appropriate definition for LWD and limits comparisons across multiple studies.

3.1.2 Scaling

Scaling refers to changing a scale in space or time (Bloschl 1995). For LWD, a scaled unit produced a standard spatial unit to compare measurements of the volume or abundance of wood across field sites. Approximately 1% of the papers reviewed for this research used time as a scaled unit. When time was used, it was always combined with a second technique such as volume of wood recruited per m^2 of stream per year (e.g. Lienkaemper and Swanson 1987). In the literature, data were commonly scaled by length and presented as the abundance of wood per 100 m of stream length (Benda *et al.* 2002). Another common scaling technique was area presented as the abundance or volume of wood per meter squared or hectare (e.g. Chen *et al.* 2006). Bankfull width, bankfull width squared, and time were also used as scaling techniques (e.g. May and Gresswell 2003, Downs and Simon 2001, Hogan *et al.* 1998). There was no consistency to the scaling and no justification of the method used.

3.2 Methods

Two datasets were used to explore these questions. The main dataset used consisted of a categorical inventory of LWD from 18 sites in the Interior of British Columbia (described in chapter 2). A second published dataset from Hinton, Alberta containing 21 field sites was used to support the findings of the dataset from the Interior of BC (Jones *et al.* 2010). The Hinton, Alberta dataset was continuous, had similar riparian composition and a smaller range in stream sizes than the BC Interior dataset.

3.2.1 The effect of definition on LWD abundance and volume

Both datasets used an inclusive initial definition for LWD. This inclusive definition allowed for several different sets of parameters to be applied to the same dataset in order to examine how changes in the parameters of the definition of LWD change the field and scaled measurements as well as the pattern.

The LWD data collected in the Interior of BC was a categorical inventory. Initially, six common definitions were applied to the categorical inventory (Table 3.1). These definitions varied from Gomi *et al.* (2001) inclusive definition to May and Gesswall (2003) exclusive definition (Table 3.1). The incremental increase in diameter and length was meant to determine which parameter was more sensitive to definition and explore the patterns of stream size with piece size. After initial exploration of the data, however; only three separate definitions for LWD were applied to the categorical dataset:

1. 0.1 m diameter 0.5 m length
2. 0.1 m diameter 1.0 m in length
3. 0.2 m in diameter and 1.0 m in length.

Definition 1 is the most inclusive and is commonly used in headwater streams (e.g. Gomi *et al*. 2001). Definition 2 is the most common in the literature and maintains the same diameter but doubles the length of the piece of wood classified as large (e.g. Murphy and Koski 1989). Finally, Definition 3 doubles the diameter used for LWD. These three definitions allow for exploration of incremental changes in diameter and length on the abundance and volume of LWD. By changing only one factor at a time and building on these changes the more sensitive parameter can be identified. For both field datasets, wood abundance and volume were scaled for each site. Each of the 18 streams was classified by bankfull width as small (<3 m), transitional (3-5 m) or medium (> 5 m) (Chen *et al.* 2006).

The continuous dataset from Hinton, Alberta was obtained in order to explore whether the patterns observed in the Interior BC were consistent between types of data or if they reflected the categories used to collect the data. Five of the six definitions initially applied to the categorical dataset were applied to the Hinton dataset (Table 3.1). The most inclusive definition used by Gomi *et al.* (2001) could not be applied since only pieces of LWD that were at least 1m long were sampled.

Table 3.1 Six definitions initially proposed to be applied the Interior of BC dataset.

Reference	Diameter (m)	Length (m)
Gomi *et al.* 2001	0.1	0.5
Murphy and Koski 1989	0.1	1.0
Hedman *et al.* 1996	0.1	1.5
Toews and Moore 1982	0.1	3.0
Young 1994	0.15	2
May and Gresswell 2003	0.2	2

3.2.1.1 Comparison of field data and scaled data

The analysis for exploring the effect of definition on the abundance and volume of wood was the same for field data and scaled data. All statistical tests used an alpha of 0.05 unless otherwise indicated. An alpha of 0.1 has been indicated for multiple tests in order to reduce the possibility of a type two error. A type two error is defined as accepting the null hypothesis when it is false.

Chi-squared tests for independence were calculated to determine whether the abundance or volume of wood at each site were independent of LWD definition. The null hypotheses used for all tests stated that the abundance or the volume of LWD measured at each stream was independent of the definition used for LWD. The alternate hypotheses used for all tests stated that the abundance or the volume of LWD measured at each stream was not independent of the definition used. The chi-squared test determined the effect of definition, however, it could not identify which definition caused the effect. To investigate the effect of definition at multiple stream sizes, the sites were divided into small, transitional and/or medium streams and the chi-squared test was recalculated. For the scaled data, the values entered into the test were small and covered either 1 m^2 or 1 m^3 of stream. The chi-squared was then re-calculated using a larger scaled area of $100m^2$ or volume of $100m^3$ to explore whether the patterns observed at a finer scale held true over a larger stream section.

Pearson Correlations are used to explore the relationship between two quantitative variables (Perez 2006). Pearson correlation matrixes were calculated to compare the effect of definition on the abundance and volume of wood measured at each site and to identify specific groupings of definitions. The quantitative variables used for the data from the Interior of BC were the abundance and volume of wood as field and scaled data for the three definitions applied to the dataset. The correlation matrix for the Interior three correlations:

1. Definition 1 * Definition 2
2. Definition 1 * Definition 3
3. Definition 2 * Definition 3.

In order to avoid the inflation of alpha and a type one error, the alpha of 0.05 was divided by the number of correlations. The data from Hinton, Alberta used five different definitions and as such the correlation matrix had 10 possible correlations. The initial matrixes included all 18 sites for the Interior of BC dataset and 21 sites for the Hinton, Alberta dataset in the correlations. To investigate the effect of definition within stream size on the correlations, the sites were divided into three stream sizes (small, transitional and medium) and the correlations were recalculated for both datasets.

3.2.1.2 THE EFFECT OF DEFINITION ON THE OBSERVATION OF PATTERN IN THE SCALED DATA

General linear models (GLM) were run to explore how the patterns in scaled abundance and volume of wood varied with stream size and definition. This was done to find out if different definitions produced different patterns across stream size. For the Interior of BC dataset a second set of models was also run to explore the effect of dividing the dataset into the wood classified as within a jam or free in the stream to see if this distinction would be effected by definition.

3.2.2 THE EFFECT OF SCALING ON LWD ABUNDANCE AND VOLUME

Scaling type and data presentation were explored at two levels. The first level involved exploring multiple scaling techniques on a single set of parameters used to define LWD. The second level involved comparing the three highest correlated scaling techniques across multiple sets of parameters used to define LWD.

Four scaling techniques were applied to both datasets using the most inclusive definition. The most inclusive definition for both datasets was used to minimize the effect of definition across multiple stream sizes. The four scaling techniques included area (m^2), volume (m^3), bankfull width squared (m^2), and length (100 m) (Table 3.2). The field data were also included in the dataset as the literature reviewed identified 30% of the papers did not scale data or mention a specific scaling technique. Scaling by volume was not used in the literature; however, it was included in the analysis for two reasons. Scaling by volume would (1) produce a dimensionless value for comparison of LWD volume and (2) account for the most stream variables and produce the most standard unit.

Scaled data was calculated by dividing the abundance measured or the volume calculated from the field data by each scaling technique (Table 3.2). Each technique calculated a different value for the scaled data, which potentially could produce a different pattern. The results for each scaling type were plotted against bankfull width for the Interior of BC dataset.

The scaling types account for morphologic differences between field sites in order to produce an unbiased comparison across sites. Pearson correlations were calculated for the abundance and volume of wood across scaling types. The correlation matrix consisted of 10 correlations and as such the alpha of 0.05 was divided by 10 in order to avoid inflation.

The three scaling techniques with the highest correlations were area (e.g. m^2), volume (e.g. m^3) and length (e.g. /100m). Pearson correlations for the abundance and volume of wood per 100 m of stream length were calculated for both the Interior of BC and the Hinton, Alberta dataset across multiple sets of parameters. The datasets were run as a whole and then divided into stream size, as was done in the previous analysis of data scaled by area and volume. The strength of these correlations was compared to values for scaling by area and volume to assess which scaling technique was the most resistant to definition. The results for the abundance and volume of wood were plotted for all three definitions and scaling types for the Interior of BC dataset.

Table 3.2 Common scaling techniques and calculation

Type of Scaling	Calculation
No scaling	N/A
Unit Area	$/(L_{survey}{}^{*} \times W_{bf}{}^{\wedge})$
Unit Volume	$/(L_{survey} \times W_{bf} \times D_{bf}{}^{\#})$
Bankfull width squared	$/W_{bf}^{2}$
100 m	$/(L_{survey} \times 100)$

* L_{survey} is the length of survey used to collect the data
^ W_{bf} isthe bankfull width for the stream
\# D_{bf} is the bankfull depth measured at each stream

3.3 RESULTS

3.3.1 THE EFFECT OF DEFINITION ON LWD ABUNDANCE AND VOLUME MEASURED IN THE FIELD

The abundance but not the volume of the field data was affected by definition (Table 3.3 and 3.4). When sites were divided into stream size categories, small and medium streams were more affected than transitional streams. The volume in small streams showed more variability between definitions than transitional or medium streams; however, this variability was not statistically significant.

For the Interior of BC, the abundance of wood measured in the field was dependent on definition at all stream sizes (Table 3.4). Small and medium streams were statistically significantly dependent on definition to an alpha of 0.05 and transitional streams were significant dependent to an alpha of 0.1(Table 3.3). Definitions 1 and 2 were significantly correlated across all stream sizes and definition 3 was only significantly correlated with definition 1 and two in transitional streams (Table 3.4). Definitions 1 and 2 both have a diameter of 0.1 m and definition 3 has a diameter of 0.2 m. Increasing the length parameter by 0.5 m had no statistical effect on the abundance of wood; however, increasing the diameter by 0.1 m had an effect on the abundance. For the Interior of BC dataset, diameter was the more sensitive parameter in the definition of LWD.

For Hinton, the abundance of measured wood in the field was dependent on definition for small streams, but not transitional streams (Table 3.3). The most inclusive definition could not be applied to this dataset, which may be the reason the differences between definitions were only to an alpha value of 0.1, but not 0.05, as observed in the dataset of the Interior of BC. In small steams, the two best definitions were Hedman *et al*. (1996) and Young (1994). The definition used by Hedman *et al.* (1996) correlated significantly with all other definitions, except May and Gresswell (2003). None of the definitions with 0.1 m diameter correlated significantly with the definition used by May and Gresswell in small streams. This is a similar pattern to the Interior of BC where definition 3 did not correlate with definitions 1 or 2. The definition used by Young (1994) correlated significantly with all definition except Murphy and Koski (1989). Young (1994) had a diameter of 0.15 m and a length of 2.0 m compared to Murphy and Koski (1989) who used a diameter of 0.1 m and a length of 1.0 m. Also, Young (1994) correlated highly with other definitions that had a diameter of 0.1 m, but the length parameters were more restrictive for these definitions (1.5 m or 3 m). Increasing the length parameter by a metre caused significant changes to the abundance of wood measured. In transitional streams, correlations were generally poor. The only significant correlation was between Young (1994) and Toews and Moore (1982). The lowest correlation was between the most inclusive definition (Murphy and Koski 1989) and the most exclusive definition (May and Gresswell 2003). For this dataset, increasing the diameter by 0.1 m had the same effect as increasing the length parameter by 1 m. For Hinton, diameter was the more sensitive parameter in the definition of LWD.

For the Interior of BC, the volume of wood measured in the field did not vary by definition at any stream size (Table 3.3 and 3.4). Small steams had the highest test statistic for the Chi-squared test and lowest correlations for the Pearson's correlation matrix, suggesting that this size was the most variable (Table 3.3 and 3.4). In small streams, the poorer correlation was between definition 3 and definition 1 or 2. This was the same trend as the abundance of wood where doubling the diameter produced poorer correlations between definitions. For volume the diameter was the more sensitive parameter in the definition of LWD.

For Hinton, the volume of wood measured in the field was not dependent on definition (Table 3.6). The best definitions for this dataset were again Hedman *et al.* (1996) and Young (1994). These two definitions had the highest correlations with all other definitions. This trend was consistent over the two stream sizes. The findings were consistent with the dataset from the Interior of BC, in that definitions with the same diameter parameter grouped together with the strongest correlations.

Table 3.3 Results from chi-squared test for independence. The values provided are the calculated test statistic including an indication of statistical significance where appropriate.

Variable	**Combined**	**Small**	**Transitional**	**Medium**
Interior of BC				
Degrees of Freedom	34	14	6	8
Critical Test Statistic	50	23	12	15
Field data				
Abundance of wood	343*	82*	10.9**	25*
Volume of wood	7.4	5.0	0.07	0.08
Scaled data				
Abundance of wood-small area#	1.078	0.536	0.004	0.004
Abundance of wood-large area@	107.8*	53.6*	0.4	0.4
Volume of wood-small area	0.081	0.066	0.0002	0.00001
Volume of wood-large area	8.1	6.6	0.02	0.001
Hinton, Alberta				
Degrees of Freedom	80	60	16	N/A
Critical Test Statistic	101	79	26	N/A
Field data				
Abundance of wood	96**	76**	21	N/A
Volume of wood	23	19	4.5	N/A
Scaled data				
Abundance of wood-small area	1.36	1.22	0.14	N/A
Abundance of wood-large area	136*	122*	14	N/A
Volume of wood-small area	0.33	0.21	0.029	N/A
Volume of wood -large area	33	21	2.9	N/A

Small Area: scaled LWD abundance by unit area (m^2) and volume by unit volume (m^3)
@ Large Area: scaled LWD abundance by 100 m^2 and volume by 100 m^3
*Alpha 0.05
** Alpha 0.1

Table 3.4 Pearson correlation results for the Interior of BC dataset. The numbers are the Pearson-R including an indication of statistical significance where appropriate

Correlation	All	Small	Transitional	Medium
Field data				
Abundance				
1*2	0.99*	0.99*	0.95*	0.98*
1*3	0.93*	0.58	0.96*	0.14
2*3	0.92*	0.56	0.96*	0.14
Volume				
1*2	0.99*	1.0*	1.0*	1.0*
1*3	0.99*	0.94*	1.0*	0.99*
2*3	0.99*	0.94*	1.0*	0.99*
Scaled data				
Abundance (#/m^2)				
1*2	0.98*	0.97*	1.0*	1.0*
1*3	0.46	0.37	0.96**	0.98*
2*3	0.45	0.33	0.95**	0.99*
Volume (m^3/m^3)				
1*2	1.0*	1.0*	1.0*	1.0*
1*3	0.99*	0.99*	0.99*	1.0*
2*3	0.99*	0.99*	0.99*	1.0*

* Alpha = 0.05
** Alpha = 0.1

3.3.2 THE EFFECT OF DEFINITION ON LWD ABUNDANCE AND VOLUME OF THE SCALED DATA

The scaled abundance but not the volume of wood was affected by definition (Table 3.3 and 3.4). When subdivided into stream size, the abundance of wood in small and transitional streams showed more variability than medium streams. The volume of wood in small streams showed the most variability; however, none of the volume measurements were significant.

For the Interior of BC, the abundance of scaled wood was affected by definition in small streams over a large stream area (#/100m^2) (Table 3.3 and 3.4). All three definitions were significantly correlated over transitional and medium stream sizes (Table 3.4). In small streams only definition 1 and 2 were significantly correlated. Definition 3 had poor correlations with both definition 1 (0.37) and definition 2 (0.33) (Table 3.4). In small streams, diameter was the more sensitive parameter to multiple definitions as increasing the diameter by 0.1 m produced poorer correlations than increasing the length by 0.5 m did.

For Hinton, the abundance of scaled wood was affected by definition in small streams over a large stream area (#/100m^2) (Table 3.3). In small streams the two best definitions were Hedman *et al.* (1996) and Young (1994). The definition used by Hedman *et al.* correlated significantly with all definitions except May and Gresswell (2003) and the definition used by Young (1994) correlated significantly with all definitions except Murphy and Koski (1989). This was the same pattern as was recorded in the field data. Increasing the diameter by 0.1 m produced poor correlations as did increasing the length by 1 m. The diameter was the more sensitive parameter in the definition of LWD. Correlations in transitional streams were generally poor with the only significant correlation being between Young (1994) and Toews and Moore (1982).

For the Interior of BC the volume of scaled wood did not vary by definition at any stream size (Table 3.3 and 3.4). Small steams had the highest test statistic for the chi-squared test suggesting that this size was the most variable (Table 3.3). The Pearson correlation's were high across all three stream sizes, however; small and transitional had poorer correlations than streams classified as medium (Table 3.4). Definition 1 and 2 had the highest correlation. Increasing the length by 0.5 m did not change the correlation; however, increasing the diameter by 0.1 produced lower correlations. Diameter was the more sensitive parameter in the definition of LWD.

For Hinton, Alberta the volume of scaled wood did not vary by definition at any stream size (Table 3.3). Most of the definitions were significantly correlated in small streams. The exception was that the most inclusive definition (Murphy and Koski 1989) and most exclusive definition (May and Gresswell 2003) were not significantly correlated. Murphy and Koski (1989) had a diameter of 0.1 m and a length of 1.0 m and May and Gressall (2003) had a diameter of 0.2 m and a length of 2.0 m. With both the diameter and the length different, determining which parameter was the reason for the correlation being non-significant involves taking into account with what definitions both were significantly correlated. Both definitions were significantly correlated with Young (1994), which had a diameter of 0.15 m and a length of 2.0 m, and with Hedman *et al.* (1996), which had a diameter of 0.1 m and a length of 1.5 m. The only difference between the definition used by Young (1994) and May and Gresswell (2003) is 0.05 m in the diameter, and this was enough to make the correlations different. The only difference between Murphy and Koski (1989) and Hedman *et al.* (1996) was 0.5 m in length and this was enough to make the correlations different. This analysis suggests that an increase in 0.05 m diameter or 0.5 m length is what made the most exclusive and most inclusive definition poorly correlated. Diameter was the more sensitive parameter as a smaller difference in diameter produces a significant difference in the volume of scaled wood. For transitional streams, all of the definitions were significantly correlated. These findings are consistent with the dataset from the Interior of BC.

3.3.3 THE EFFECT OF DEFINITION ON THE SPATIAL PATTERNS IN SCALED DATA

The abundance and volume of wood measured varied between stream size and definition in both datasets (Table 3.5, Fig 3.1 3.2). Comparisons between jammed and free wood in the Interior of BC dataset also showed significant variance between definition and stream size for the abundance of wood but not the volume.

3.2.3.1 THE PATTERNS IN LWD ACROSS STREAM SIZE AND DEFINITION

For the Interior of BC the abundance of wood varied within definition by stream size and within stream size by definition (Table 3.5). In small streams, definition 3 had a lower mean than definition 1 or 2 (Table 3.5). The diameter used for definition 3 was 0.2 m while definition 1 and 2 had a diameter of 0.1 m. For all three definitions, medium streams had significantly lower mean values than transitional or small streams (Table 3.5, Fig. 3.1). The pattern in the abundance of wood over stream size was dependent on the definition (Fig 3.1). Definitions 1 and 2 had a decreasing pattern with stream size that is consistent with current literature (e.g. Hassan *et al*. 2005 Chen *et al.* 2006). Definition 3 had a larger mean abundance of wood in the transitional streams (3-5 m) than in smaller streams. The doubling of the diameter from definition 2 to definition 3 caused changed the abundance of wood and the trend over stream size. This change was not observed when the length doubled from definition 1 to definition 2. Diameter was a more sensitive parameter than length in the definition of LWD.

For Hinton, Alberta the abundance of scaled wood varied across definition (P-value 0.0003) and stream size (P-value <0.0001) (Fig 3.2). The most exclusive definitions did not equal the most inclusive definitions (Fig 3.2). In small streams definitions with the same diameter parameter grouped together. For small and transitional streams the definition used by May and Gresswell (2003) had a diameter of 0.2 m and had significantly smaller mean values than the definition by Murphy and Koski (1989) or Hedman *et al.* (1996) which both had diameters of 0.1 m. Additionally in small streams, the definition used by Murphy and Koski (1989) had a significantly larger mean values than the definition used by Young (1994) which had a diameter of 0.15 m. All other combinations of definitions were not significantly different within stream size. The trend was similar across stream size for all definitions; however, the more exclusive definitions had a smaller decrease in abundance of wood with increasing stream size than the more inclusive definitions. The Hinton, Alberta dataset had a similar pattern to the dataset from the Interior of BC.

For the Interior of BC the volume of scaled wood varied by stream size but not by definition (Table 3.5). For all three definitions, transitional streams had significantly larger mean values than small or medium streams (Table 4.5) (e.g. Chen *et al*. 2006). Even though the values were different across definition, the trend across stream size was the same.

In Hinton, Alberta the volume of scaled wood varied across definition (P-value <0.0001) and stream size (P-value 0.0004). In the small streams, two groups of definitions were apparent. The definitions of Murphy and Koski (1989) and Hedman *et al.* (1996) grouped together and both had diameters of 0.1 m with lengths < 2 m. In transitional streams, the definition used by May and Gresswell (2003) had a significantly smaller mean than definitions used by Murphy and Koski (1989) or Hedman *et al.* (1996). Additionally, the definition used by Murphy and Koski (1989) had a larger mean than Toews and Moore (1982). Even though the values were different, the pattern from small to transitional streams was the same across definition.

Table 3.5 Interior of BC mean and standard deviation of abundance and volume of wood across definition by stream size.

Definition	Small	Transitional	Medium
Abundance			
1	0.77 ±0.32	0.37± 0.17	0.10±0.04#
2	0.71± 0.31	0.35±0.16	0.10±0.03#
3	0.15±0.13*	0.22± 0.12	0.06±0.02#
Volume			
1	0.17±0.16	0.36± 0.45*	0.07±0.04
2	0.17± 0.16	0.36± 0.45*	0.07± 0.04
3	0.13±0.17	0.35± 0.45*	0.07± 0.04

* Significantly different mean across definition within stream size
# Significantly different mean across stream size within single definition

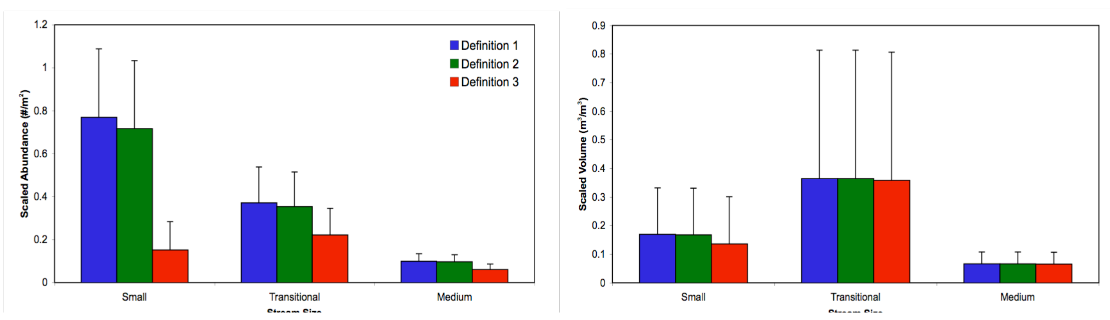


Fig 3.1 Comparison of the mean abundance and volume of scaled wood by each definition across stream size classes (mean and standard deviation) for the Interior of BC dataset. The multiple definitions affected the abundance of wood more than the volume.

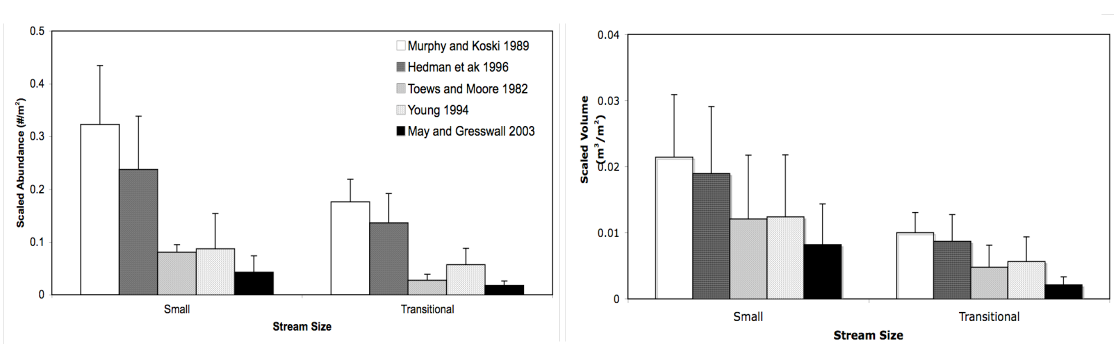
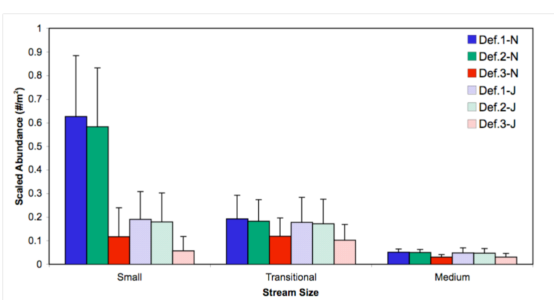


Fig 3.2 Comparison of the mean abundance (left) and volume (right) of scaled wood by each definition across stream size classes (mean and standard deviation) for the Hinton, Alberta dataset. The abundance of wood was more affected by definition than the volume.

3.3.3.2 Patterns in the LWD across jams, definition and stream size

For the Interior of BC the abundance of scaled wood varied in jammed and free wood by stream size and definition (Fig 3.3). In small streams, definition 3 had significantly smaller values for free and jammed wood than definition 1 or 2 (Fig 3.3). In small streams, definition 1 and 2 had a significantly lower mean for wood in jams than free in the stream (P-value <0.0001). Definition 3 had no trend in small streams across jammed and free wood (Fig 3.3). Jammed wood has a similar pattern across stream size for all three definitions. Jammed wood had similar mean values for small and transitional streams and decreased for medium streams. The abundance of free wood decreased with stream size for definitions 1 and 2. For definition 3, small and transitional streams had similar mean values that were significantly larger than medium streams.

The volume of scaled wood did not vary by definition, stream size or jam (Fig 3.3). All three definitions had a peak in volume of scaled wood in transitional streams. This result occurred both in the wood classified as jammed and the wood classified as free and was consistent with the current literature (Chen *et al.* 2006). Even though the result was not significant, the volume of scaled wood in jams in medium streams was higher than free wood for all three definitions. This stream size had the closest mean values between jammed and free wood and was the only stream size that jammed wood had a higher mean (Fig 3.3). The pattern for all three definitions suggests the relative volume of wood associated with jams increases with an increase in stream size.



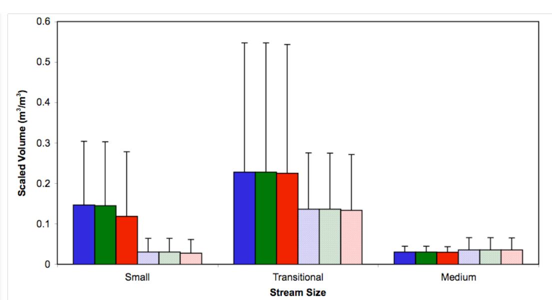


Fig 3.3 Comparison of the abundance (left) and volume (right) of wood analyzed measured by each definition across stream size and jam classes (mean and standard deviation). "N" indicates the class was not associated with jammed wood and "J" indicates that the class is associated with jammed wood.

3.3.4 The effect of scaling on LWD abundance and volume

3.3.4.1 Comparison across scaling type within definition

Scaling type affected the abundance and volume of wood across stream size and definition. All of the scaling types were significantly correlated for the abundance and volume of wood for the Interior of BC dataset (Table 3.6). The best correlations were between unit area (m^2) and volume (m^3). The poorest correlation for abundance was between bankfull width squared and length. For the volume, the poorest correlation was between unit volume and length. None of the scaling types were significantly correlated with the field data. For the field data, the abundance of wood increased with increasing stream size, and all scaling types had a decreasing pattern in the abundance of wood with increasing stream size (Fig 3.4). The increase in wood in the field data may be explained by two reasons. First, the survey length at each site was calculated as 50 times the bankfull width, so increases in stream size increased the length of riparian zone able to recruit wood into the stream. Second, an increase in stream size increased the total stream area able to store wood. The volume of wood scaled by length was low across increasing stream sizes and had little variability (Fig 3.4). The volume of wood scaled by area and volume was highly variable in streams < 3 m and had a decreasing pattern in streams > 3 m (Fig 3.4). Figure 3.4 highlights that the choice in scaling technique can determine the trend observed.

For the Hinton dataset, none of the abundance correlations were significant and only two of the volume correlations were significant (Table 3.6). The bankfull depth was not measured at any of the field sites; this limited the comparison of scaling types to area, bankfull width squared, and length. The greatest correlations for the abundance and volume were between bankfull width squared and area. The poorest correlations for both abundance and volume were between bankfull width squared and length. The values scaled by length were significantly correlated with the field data. This could be a result of the fact that all of the field survey lengths were between 50 and 65 m, making them approximately a standard length unit.

Table 3.6 Pearson R results for Interior of BC and Hinton, Alberta data comparing multiple scaling techniques using a single definition of LWD

Correlation Parameters	Interior of BC	Hinton, Alberta
Abundance		
Volume*Area	0.95*	N/A
Volume* Bankfull width squared	0.88*	N/A
Volume*100 m	0.78*	N/A
Area *Bankfull width squared	0.94*	0.14
Area* 100 m	0.83*	0.05
Bankfull width squared* 100 m	0.73*	0.04
Volume		
Volume*Area	0.97*	N/A
Volume* Bankfull width squared	0.97*	N/A
Volume*100 m	0.74*	N/A
Area *Bankfull width squared	0.96*	0.81*
Area* 100 m	0.76*	0.57*
Bankfull width squared* 100 m	0.80*	0.17

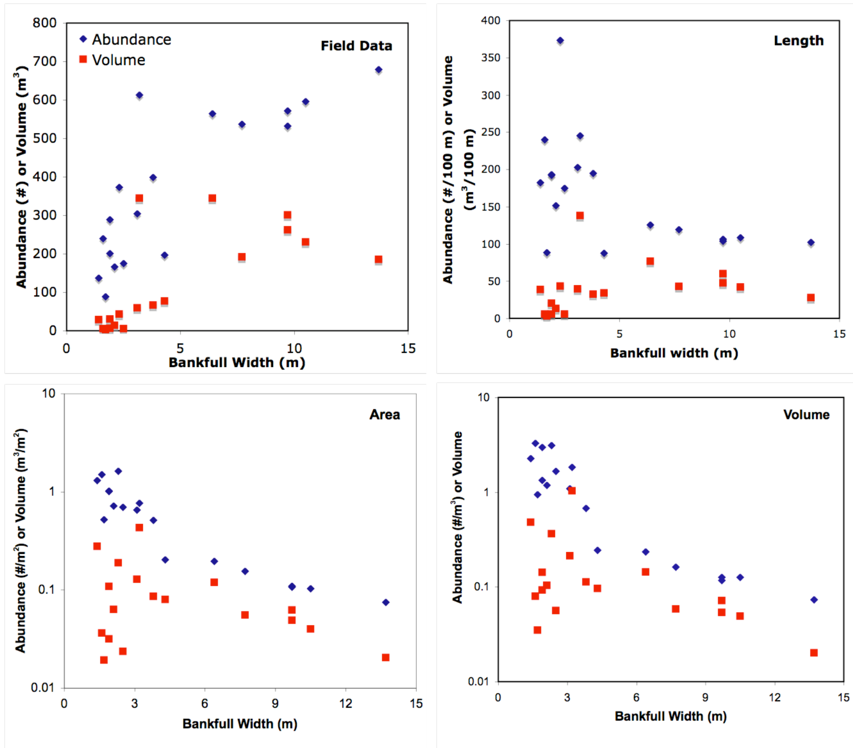


Fig 3.4 Comparison of the trends with bankfull width for the abundance and volume of scaled wood for the Interior of BC dataset. The field data with no scaling has also been plotted for comparison. For the abundance of wood, length, area and volume have a similar decreasing trend with increasing stream size. Volume and area have a similar pattern for the volume of wood, however this pattern is different then scaling by length.

3.3.4.2 Comparison of three scaling types across multiple definitions

The scaling techniques of length, area and volume were chosen for comparison across definition to determine which scaling technique was the most resistant to definition (Table 3.7). The scaling type with the most and highest significant correlations across stream size and definition is the technique most resistant to definition. The abundance of wood was sensitive to scaling type and definition. The volume of wood was not affected by scaling type.

In the Interior of BC, scaling by length had poorer correlations than scaling by area for the abundance of wood (Table 3.7). When divided into stream size, small streams had the highest variation in the abundance of wood between definitions. The scaling technique of a length had one less significant correlation within stream size than scaling by area. The trend in the data with stream size was different scaling by length than scaling by area or volume (Fig 3.5). When scaled by length, definition 1 and 2 decreased slightly to 3-5 m bankfull width and then had no decreasing trend in the data (Fig 3.5). When scaled by area or volume, definition 1 and 2 decreased with stream size across all ranges of bankfull widths in the study sites. For definition 3, when scaled by length, area or volume the values were variable in streams with bankfull width < 3 m, and mimicked definition 1 and 2 for streams with bankfull width > 3 m. The most variability between definitions for all scaled units was in streams with bankfull width < 3 m. Some of the values for definition 3 were an order of magnitude lower than measurements for definition 1 or 2. For streams with bankfull width > 3 m, definition 3 mimicked the definition 1 or 2 with slightly lower values. Length produced a different pattern. A larger difference in the values was measured for each definition and had fewer significant correlations than area or volume. For these reasons, abundance should be scaled by length or volume. The volume of wood was not statistically different between scaling types across definition and had a similar trend in the data with increasing stream size (Table 3.7 and Fig 3.5). The Pearson correlations were the same across definition for all scaling types (Table 3.7). Streams with bankfull width < 3 m had the most variability in the scaled values across definition and scaling type (Fig 3.5). In streams with bankfull width > 3 m, values scaled by length decreased slightly with increasing stream size and values scaled by both area or volume decreased strongly with increasing stream size (Fig 3.5). Volume was the best scaled unit because it had the most overlapping variables and the smallest range in values.

For Hinton, Alberta the abundance and the volume of wood scaled by length was poorly correlated across definition by comparison to the measurements scaled by area. In small streams, the definition used by Hedman *et al.* (1996) and Young (1994) were the best for both length and area. Hedman *et al*. (1996) correlated significantly with all definitions except May and Gresswell (2003). Young (1994) correlated significantly with all definitions except Murphy and Koski (1989). In transitional streams, the only significant correlation was between Young (1994) and Toews and Moore (1982). For scaling by length, the poorest correlation in transitional streams was between Murphy and Koski (1989) and May and Gresswell (2003) with a Pearsons correlation coefficient of 0.12.

For the volume of wood per 100 m, small streams showed no difference between definitions. Transitional streams had one significant correlation between Young (1994) and Toews and Moore (1982). The patterns in the small streams were similar to the data scaled by area; however, the correlations were generally poorer.

Table 3.7 Pearson Correlation results. Gives the Pearson's R. * alpha 0.05 # indicates where the correlation is different for length than for other scaling types

Correlation	**All**	**Small**	**Transitional**	**Medium**
Abundance scaled by length (#/100m)				
1*2	0.98*	0.99*	1.0*	1.0*
1*3	0.20#	0.46#	0.96**	0.98*
2*3	0.18#	0.44#	0.92#	0.99*
Volume scaled by length (m^3/100m)				
1*2	1.0*	1.0*	1.0*	1.0*
1*3	0.99*	0.99*	0.99*	1.0*
2*3	0.99*	0.99*	0.99*	1.0*
Abundance scaled by area (#/m^2)				
1*2	0.98*	0.97*	1.0*	1.0*
1*3	0.46	0.37	0.96**	0.98*
2*3	0.45	0.33	0.95**	0.99*
Volume scaled by volume (m^3/m^3)				
1*2	1.0*	1.0*	1.0*	1.0*
1*3	0.99*	0.99*	0.99*	1.0*
2*3	0.99*	0.99*	0.99*	1.0*

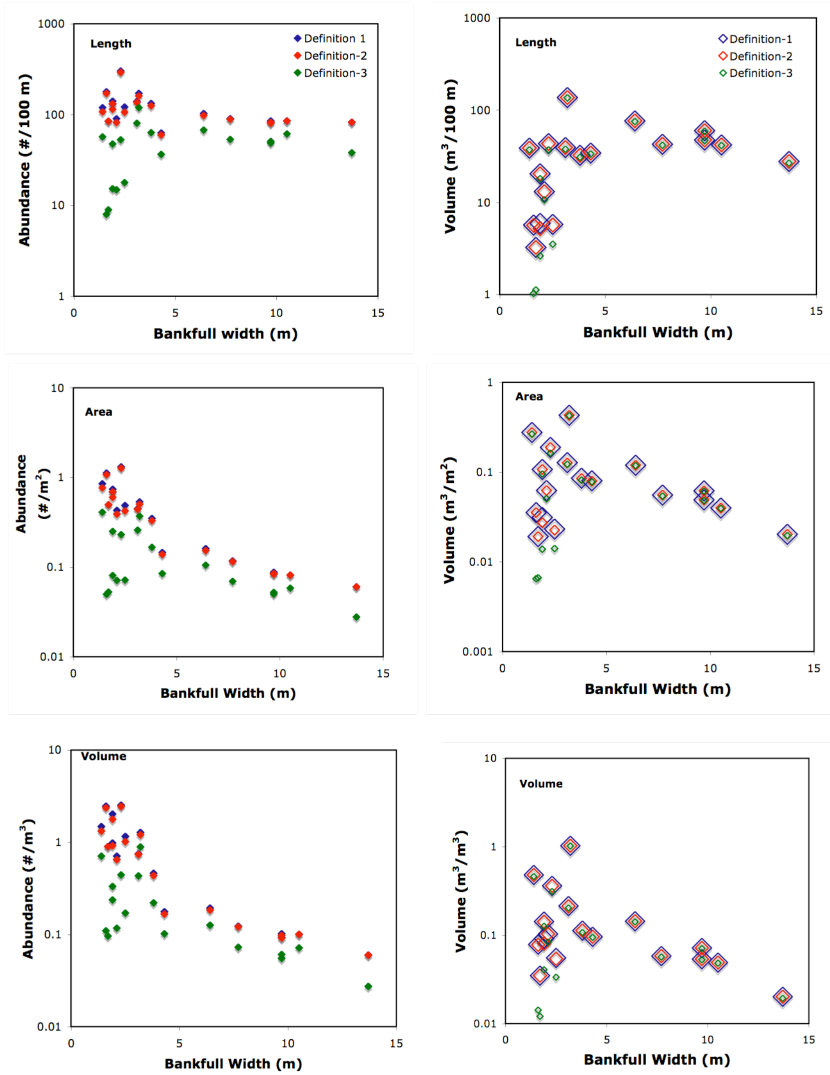


Fig 3.5 A comparison in LWD across definition and scaling type. For the abundance of wood, definition one and two were the best correlated across all scaling types. For streams < 3 m the variability between definitions was higher then for streams > 3 m bankfull width. The volume of wood is plotted as outlined diamonds of varying sizes with colours corresponding to the abundance measured. The diamonds vary in size so that nested values can be observed, because the volume measurements across definitions overlapped. For the volume, streams < 3 m were more variable across definition for all scaling types.

3.4 Discussion

This chapter is an initial attempt to understand the affect of the variability in parameters used to define LWD and scaling methods used to analyze and present results on the abundance of LWD in streams. The goal was not only to understand the effect but also to determine the analysis and data presentation most resistant to differences among definitions of LWD. The remainder of this chapter will discuss the four main findings of this study and how they fit within the current literature.

The four main conclusions of this chapter are:

1. Small streams (<3 m) are the most sensitive to the definition of LWD. Medium streams (>5 m) are the least sensitive.
2. The abundance of wood measured in a stream is more sensitive to definition than the calculated volume.
3. The diameter used to define LWD is a more sensitive parameter than length.
4. Scaling by length (e.g. number per 100 m) is more sensitive to definition than scaling by area or volume.

Even though these are written as four separate statements, they are linked across space and scale. Where appropriate they will be discussed together within the hierarchy of the watershed.

3.4.1 Stream size

Throughout this chapter, small streams have been more sensitive to definition than either transitional or medium streams. This sensitivity may be explained by looking at how the median length and diameter of wood in the streambed changes with stream size (Table 3.8). All definitions that used a diameter >0.1 m measured less than half of the abundance of wood than studies that used a diameter ≥ 0.1m, regardless of stream size. If the object of the study were only to estimate the volume of largest wood then the more exclusive definition (diameter >0.1m) could be used and more than half of the wood would be measured. Definition 3 applied to the Interior of BC data repeatedly had the lowest values and was the only definition with a diameter >0.1 m. In small streams, the trend was different for definition 3 than either of the other two definitions. In the Hinton dataset, the definitions used by Young (1994) and May and Gresswell (2003) correlated the highest and were the only definitions with a diameter >0.1 m.

Table 3.8 Median size of wood in terms of diameter and length across stream size. The diameter and length values represent the minimum size measurement for the categories used to collect the data. For abundance this was determined as the size class that reached 50% of the number of pieces measured at each site. For volume, this was determined as the size class that reached 50% of the volume calculated for each site.

Stream Size	**Diameter (m)**	**Length (m)**
Abundance		
<3 m	0.05-0.1	0.5-3
>3 m	0.1	1-3
Volume		
<3 m	0.1-0.55	1-3
>3 m	0.55	5-10

Median size of wood increases with stream size (Chen *et al.* 2006). In larger streams, if more inclusive definitions were used (e.g. 0.1 m diameter, 0.05 m in length), proportionally very few of these small pieces would be present in the stream, causing the definitions to produce less of a difference in absolute values. In smaller streams where the discharge is low and many of the pieces are large compared to the bankfull width, small pieces could easily become jammed or stored making a more inclusive definition more important (Brauderick and Grant 2000, Gurnell 2003).

3.4.2 ABUNDANCE AND VOLUME MEASUREMENTS

The abundance of wood measured is more sensitive to definition than the volume of wood. More inclusive definitions add small pieces with low volumes. Unless a large number of small pieces are added, these pieces make little difference in the in-stream volume of wood. The size of wood associated with the median volume of wood was larger than the size of wood associated with the median number of pieces of wood (Table 3.8). For example, in streams > 3 m, the diameter associated with the median volume was 0.55 m, where for the median abundance was 0.1 m. A diameter parameter defined as >0.1 m would account for more than half of the volume of wood in the stream, but not necessarily more than half of the number of pieces. This is reflected in the results, which showed the volume of wood to be much less sensitive to definition than number of pieces.

Chen *et al*. (2006) found that small streams had a high density of wood and a low volume, transitional streams had a moderate density of wood and a high volume and medium streams had both a low density and volume of wood. Chen *et al*.'s (2006) findings highlight why the number of pieces varies more than the volume of wood. The number of pieces ranges from high to low density with increasing stream size, where the volume of wood has a smaller range, starting low, moving to moderately high and then returning to low. The volume of wood is related to the size of pieces and strongly influenced by the largest logs, which are included regardless of the definition and minimum criteria for LWD diameter and length. In contrast, the number of pieces is a count of all pieces of LWD and since small pieces are more common than large pieces, it is reliant on the definition of the minimum size parameters of LWD to be included in a study. Due to transport capacity, smaller streams are also much more variable in the number and volume of pieces in a stream, making it easier to predict numbers in larger stream sizes.

3.4.3 Diameter and length parameter of definition

For the Interior of BC dataset, moving from definition 1 to 2 increased the piece length by 0.5 m and had little impact on the abundance or the volume of wood measured in the stream. Doubling the diameter (0.1 to 0.2) from definition 2 to 3 caused significant differences in the abundance and the patterns observed in the dataset. This finding was reflected in the Hinton dataset where the definitions with 0.1 m diameter generally grouped together and smaller incremental changes in the diameter caused more difference than larger changes in the length parameter. The definition used by Young (1994) had a diameter of 0.15 and a length of 2.0 m, while May and Gresswell (2003) had a diameter of 0.2 m and a length of 2.0 m. Young (1994) correlated well with the definitions that used 0.1 m and May and Gresswell (2003) correlated very poorly with all of the definitions. The only difference between these two definitions is 0.05 m in the diameter; further suggesting that diameter is an important factor.

With definitions of LWD in the literature including diameters ranging from 2.5 to 20 cm the fact that small changes in diameter produce significant differences in the abundance and volume of wood is relevant. The difference was more prominent in smaller streams. This suggests a more inclusive diameter definition should be used in smaller streams and comparisons across studies in small streams should be conscious of the effect of definition. The differences in measured values due to diameter and length parameters in the definition of LWD decrease with increasing stream size. This may reflect the transport of wood downstream. In larger streams, if smaller pieces of wood can be transported, than using a more exclusive definition (e.g. May and Gresswell 2003) would measure the same abundance of wood as using an inclusive definition (e.g. Murphy and Koski 1989).

3.4.4 Scaling techniques

If only one definition of LWD was in use and only one stream size was being looked at then scaling by area (e.g. m^2), volume (e.g. m^3) or length (e.g. /100 m) would be appropriate. When comparing across stream sizes, however scaling by reach length does not account for geomorphology, may inappropriately weight values, and produces different patterns in the data compared to other scaling methods. When comparing across multiple definitions, scaling by length was more sensitive to definition than scaling by area or volume. Hassan *et al.* (2005) compared scaling by length to scaling by area and reported that the pattern produced by area was a clear decrease in LWD with stream size, where as scaling by length was more variable.

An argument for using length is that it produces an easily manageable number, whereas scaling by area or volume could produce a small number that may be more difficult to conceptualize over a larger area. This problem was averted by Chen *et al.* (2006) who presented their findings in terms of pieces per $100m^2$ and by Jones and Daniels (2008) who used volume per hectare.

The fact that scaling by length is more sensitive to the definition of LWD than scaling by area or volume has serious implications for previous research that compared LWD among streams. Scaling by length was the most common technique and was used to compare multiple stream sizes in papers. The example in Chapter 1 and the results of this chapter show that scaling by length can produce a different pattern in the data than other techniques and this scaling technique does not produce as standard a scaled unit as area or volume.

3.5 Conclusions

The introduction to this chapter presented three questions that highlight fundamental gaps in research on LWD. This section will synthesize the knowledge gained from this chapter in order to understand the effects of multiple definitions and scaling types on knowledge of LWD.

The first question asked if there was an acceptable definition for LWD in the literature. Currently there is no accepted single definition or framework of definitions in the literature. The most common definition is 0.1 m diameter and 1.0 m in length. This research has shown repeatedly that diameter is more sensitive than length and as such the best single definition that can be compared across multiple definitions and stream sizes is 0.1 m diameter and 1.5 m in length. This definition was used by Hedman *et al.* (1996) and correlated well with all other definitions except May and Gresswell (2003). This suggests that using a definition of 0.1 m diameter and 1.0 m length would allow for comparison with most of the literature. Having the inclusive definition of 0.1 m diameter and 1.0 m length would allow for subsets of the data that describe larger LWD to compare the finding with more exclusive definitions, while still being able to make direct comparison to the most common definition.

Also, I recommend research studying the mean functional size of wood and the identification of transport capacity as a guide for a framework or scaled definition. This research has shown that in streams 3-5 m bankfull width seem to be a transition where the effect of definition decreased, suggesting that transportation of wood becomes important at this size of stream. This research has also shown that accounting for increasing numbers of geomorphic features such as bankfull flow depth and bankfull flow width produced clearer spatial patterns that accounted for the most differences between study sites. This finding supports the idea of a scaled definition because if these features were incorporated into the definition of LWD, then comparisons across study sites would be easier as differences in stream size would already be taken into account.

The second question asked if the variety of definitions in the literature affected the results in the literature. This question can be answered by considering the affect of stream size and the LWD values presented. Small streams were more sensitive to definition than larger streams. Research on small streams should be more aware of definition especially when comparing results to other research. The abundance of wood was more sensitive to definition than volume of wood. When comparing results among studies that use different definitions of LWD, volume should be the primary comparison value, then abundance as a secondary value. The definition used does affect the results reported in the literature.

The third question asked if there was a standard way that wood should be presented, a way that would minimize the effect of definition. The parameters of the definition, stream size, measured values presented, and unit used to scale and analyze the data are all important to consider when reducing the affect of definition. Diameter is more sensitive than the length to definition. All definitions that used 0.1 m as a minimum diameter were well correlated and had similar values. Researchers could potentially compare results from studies that had the same diameter definition, but not the same length. Small streams were more sensitive to definition than transitional or medium streams. If small streams are being studied a more inclusive definition may be justified. If multi-scale studies are being conducted the definition of LWD should be scaled to the smallest stream size of absolute values are being compared. Presenting and analyzing a dataset scaled by volume or area reduced the sensitivity of definition. When compiling data for a meta-analysis these scaling techniques should be used to produce the least biased results.

This chapter has suggested that even though fundamental gaps exist in the knowledge of LWD, tools can be used to reduce the effect of definition when comparing research. There is a vast amount of data collected based on LWD and there are techniques that will allow for meta-analysis and further understanding in the field. Definition does affect the wood measured in the streams, but with careful planning and proper analysis, these differences produced by definition can be minimized.

4 INFLUENCES OF STREAM SIZE AND FOREST TYPE ON LWD DISTRIBUTION

4.1 INTRODUCTION

The riparian forest and physical stream characteristics both influence the abundance and distribution of LWD in streams (Gurnell *et al.* 2002, Chen *et al.* 2006). Hassan *et al.* (2005) stated that changes in ecosystem characteristics have a confounding effect on the study of LWD. In this chapter, linkages between the riparian forest, the stream characteristics and LWD abundance and volume are explored. The 18 study sites were located in two biogeoclimatic (BEC) zones and three stream sizes. This design allowed for the exploration of two research questions to determine the most important characteristic of LWD in streams.

1. For the 18 field sites, is forest type or stream size the most important factor influencing LWD abundance and distribution?
2. Can the volume and abundance of LWD be estimated using riparian forest and/or stream characteristics?

The two research questions were designed to explore the linkages and produce a more clear understanding of how LWD changes with forest type and stream size. The research questions led to three specific focus areas that guided the research. The first section focuses on the diameter distribution of trees in the riparian forest in contrast with the LWD to assess if and how the LWD distribution reflects the riparian zone. The second focus is on the specific characteristics of the riparian zone and the stream in order to assess (1) how the riparian forests are different across forest type and (2) how the stream characteristics are different across stream size. The third focus identifies what specific riparian forest and stream characteristics affect LWD abundance and volume in order to produce predictive models.

4.2 METHODS

Eighteen sites were sampled, nine sites in the Sub Boreal Spruce (SBS) and nine sites in the Sub Boreal Pine Spruce (SBPS) BEC zones (for detailed see chapter 2). Throughout this chapter, sites in the SBS zone will be referred to as the spruce forest and sites in the SBPS zone will be referred to as the pine-spruce forest. Of the nine sites in the spruce forest, six were classified as medium-sized and three as transitional-sized streams. In the pine forest, eight sites were classified as small-sized and one as transitional-sized. Although there were nine sites in each forest type, the distribution of stream sizes within forest type was not even and produced an imbalance in the research design with respect to stream sizes within forest types which restricted some of the analyses. For example, the interaction between the influence of forest type and stream size could not be analyzed. Therefore, the relations between riparian characteristics and the stream characteristics were assessed as well as the relations between riparian and stream characteristics. This was done without classifying the data by stream size or riparian forest in order to use riparian or stream characteristics to infer stream size or riparian forest as an influence. In this approach, riparian and stream characteristics were used as proxies for forest type and stream size.

Data summaries and calculated variables used throughout this chapter were explained in Chapter 2. Most statistical tests used an alpha of 0.05; an alpha of 0.1 has been indicated for multiple tests in order to reduce the possibility of a type two error. A type two error is defined as accepting the null hypothesis when it is false.

4.2.1 DIAMETER CLASS DISTRIBUTION

The LWD size data were collected using categories that related to wood diameter (Table 4.1). The frequency of LWD in each size class was calculated for all sites. This was done by dividing the estimated number of LWD in each size class by the total number of LWD at each site. In order to compare the frequencies of the riparian trees with the LWD, the riparian data were classified into the same diameter classes as the LWD (Fig 4.1). The frequency of each size class was then calculated. The diameter distributions were compared using visual observations between the riparian trees and the LWD at each site, between forest types, and among stream sizes. If the distribution of diameter classes of the LWD was similar to that of the riparian forest, then it was assumed that the riparian forest was a dominant factor in the input and distribution of wood (Fig 4.1). If the LWD distribution did not reflect the riparian distribution, then some re-organization within the stream may have occurred, making the stream a dominant factor due probably to fluvial transport of wood (Fig 4.1). Fig 4.1 represents an expected distribution of stream-controlled and riparian-controlled LWD compared to the riparian zone distribution and was developed as a conceptual model as a point of comparison to the actual data measured at each site. For the riparian-controlled distribution, the frequency of the size classes of LWD reflects the size distribution of trees in the riparian forest (Fig 4.1). For this distribution, the assumption was made that wood pieces entering the stream would not be fluvially transported down stream or significantly redistributed by the flow (Gurnell *et al.* 2002). A majority of LWD recruitment models assume uniform direction of tree fall and a size distribution of trees based on the riparian forest, suggesting that if no transport occurred, the distribution of in-stream LWD should reflect the riparian distribution (e.g. Van Sickle and Gregory 1990, Soboto *et al*. 2006). For the stream-controlled distribution of LWD, the relative frequency of size classes for LWD reflected reorganization of wood and transport of smaller pieces downstream (Fig 4.1) (May and Gresswell 2003). At a given reach, transport of LWD increases the mean size of wood in the stream relative to the riparian zone (Chen *et al*. 2006). This suggests a stream-controlled distribution would have higher frequencies of larger pieces of wood than a riparian-controlled distribution. The median frequency of each diameter class within forest type for the riparian zone and within stream size for the LWD was also calculated.

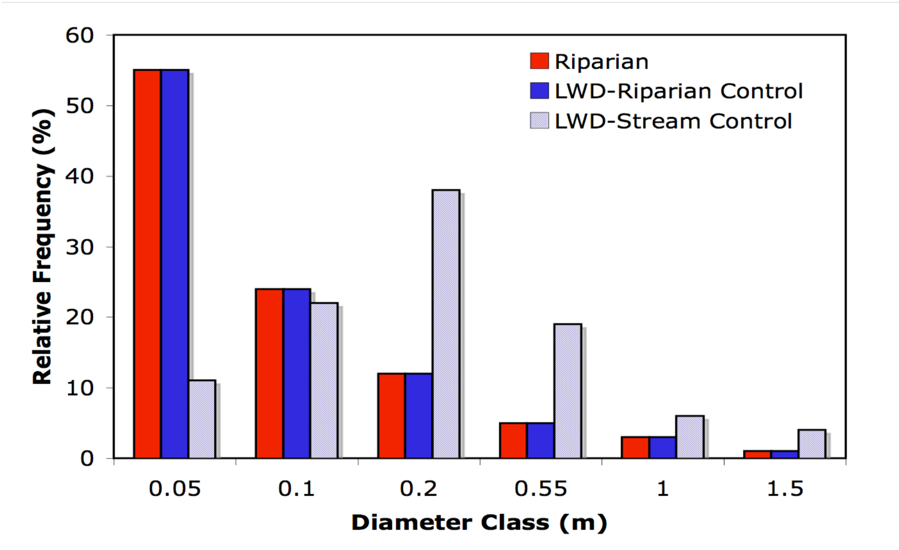


Fig 4.1 Idealized diameter class distributions. Red represents a hypothetical riparian forest. Dark blue represents a LWD distribution controlled by the riparian zone. Light blue represents a LWD distribution controlled by the stream transport and organization. The diameter class categories that were used to calculate the LWD abundance and volume have been used in this figure. These categories represent the minimum value of a range of values were classified for each category: (1) 0.05: ≥0.05-0.09; (2) 0.1: ≥0.1-0.19; (3) 0.2: ≥0.2-0.54; (4) 0.55: ≥0.55-0.99; (5) 1.0: ≥1.0-1.49; and (6) 1.5: ≥1.5.

4.2.2 Riparian forest and stream characteristics

General Linear Models (GLM) were used to test for (1) difference in riparian forest characteristics between two forest types, (2) differences in geomorphology between streams of three different sizes and (3) variation in scaled abundance and volume of LWD between forest type and among stream sizes. Logarithmic transformations were used on many of the continuous variables in order to meet the assumptions of equal variance and normality. All figures are presented in the original units.

The first set of GLM's was designed to test the differences in composition and structure between the two forest types. Characteristics that related specifically to the species in the riparian zone included: Simpson's Diversity Index, Shannon H1 and H2 Index, and calculated importance values for all deciduous trees combined, lodgepole pine (*Pinus* *contorta),* white, Sitka and hybrid spruce (*Picae glauca* and *sitchensis)* and Douglas-fir (*Pseudotsuga menziesii*). Lodgepole pine (*Pinus contorta*) and spruce (*Picae glauca* and *sitchensis* combined) had low importance values and was only located in the pine-spruce forest and in the riparian zone of the spruce forests, respectively. The characteristics related to the structure of the riparian forest included: mean basal area per stem, basal area per hectare, and stems per hectare (Appendix C). The importance values of these species would have been impossible to compare across forest type because they only occurred in one forest type.

The second set of GLM's was designed to test the morphologic differences between three stream sizes. Several characteristics used for the GLM's were averaged over each stream reach. These included: bankfull width (m), bankfull depth (m), slope (m/m) and D_{95} (mm) (Appendix 3). Also, the frequency of riffle and pool units as a distance along the thalweg and change in elevation along the thalweg were used to compare morphology at the three stream sizes. Riffle and pool units were chosen for this set of tests as these units have been studied in relation to LWD accumulations (e.g. Mossop and Bradford 2004). The longitudinal profile surveyed for each study site was used to calculate the frequency of morphologic units. Frequency for each morphologic unit was calculated as both a distance and change in elevation along the thalweg. The units will be identified as elevation-riffle or pool and distance-riffle or pool within figures and the text.

A final set of four GLM's was used to analyze the abundance and volume of wood measured at each site to determine if forest type or stream size explained more of the variability. In the GLMs, both stream size and forest type were converted to qualitative dummy variables and used as predictor variables to quantify variation in LWD (Kutner *et al*. 2005). Because of the unbalanced study design, the interaction between forest type and stream size could not be analyzed. Instead, the results from each GLM were compared using the R^2- and P-values for the full model statement, the intercept and the qualitative dummy variables representing either forest type or streams size. The assumptions of normality of the residuals, equal variance and linearity were also assessed for each test. This analysis could not identify which factor was more important as the interaction could not be tested, but it was able to identify which class variable by itself explained more of the variability in the dataset.

4.2.3 LWD ABUNDANCE AND VOLUME

A stepwise regression technique was used to identify possible predictor models for the abundance and volume of LWD and explore the relative importance of geomorphic stream and riparian forest variables. A similar approach was used by Jackson and Sturm (2002). Stepwise regressions identify significant variables from a large pool of potential predictor variables (Kutner *et al.* 2005). Stepwise regressions use an automatic search procedure to develop the best subset of variables through an iterative procedure that sequentially adds or removes variables from the equation (Kunter *et al.* 2005). The stepwise selection tool used either added or subtracted variables with each step to produce the 'best' equation (Kunter *et al*. 2005, SAS 9.1). The default alpha identified for each variable of this test for the statistical package used was 0.15, regardless of the R^2 produced (SAS 9.1). The selection of variables for each model was based on producing the best R^2, and as such, the suggested models may have eliminated potentially good models (Kutner *et al.* 2005). The subset of parameters identified as important by the stepwise regression procedure was therefore used as a starting point for understanding the links in the data and fitting a strong regression (Kutner *et al.* 2005).

Nine riparian forest and eight stream characteristics were used as potential predictor variables of the scaled abundance and volume of wood. All variables were included as both $\log_{10}$ transformed and non-transformed values. The riparian characteristics were:

1. Biodiversity indexes
    a. Simpson's Diversity Index
    b. Shannon H1 Index
2. Importance values of species
    a. All deciduous tree species combined (%)
    b. Douglas-fir (%)
    c. Lodgepole pine (%)
    d. All spruce species (white, Sitka and hybrid) (%)
3. Structural characteristics of the riparian forest
    a. Mean basal area per stem (m^2/stem)
    b. Stems per hectare of riparian forest (#/ha)
    c. Density per hectare of riparian forest (m^2/ha)

Deciduous tree species were grouped into a single importance value because deciduous trees decompose faster than conifers and play a less important role in affecting geomorphology of streams than conifers (Gurnell 2003).

The stream characteristics were:

1. Attributes averaged for individual reaches
    a. Bankfull width (m)
    b. Bankfull depth (m)
    c. Slope (m/m)
    d. D_{95} (mm)
2. Frequency of morphologic units in terms of distance and elevation along the thalweg
    a. Riffle
    b. Pool
    c. Glide
    d. Cascade

For the abundance of wood, two step-wise regressions were calculated. The first regression used the variables to predict the scaled abundance of wood. The second regression used the variables to predict the transformed (log base 10) scaled abundance of wood. Transforming the response variable is useful when the distributions of error terms are skewed and the variance of error terms is not constant (Kutner *et al.* 2005). The study sites had high spatial variance, as they were located in three stream sizes and two forest types. Transforming the scaled abundance of wood for the second stepwise regression was done so that the results of the transformed and non-transformed procedure could be compared to determine which response variable fit the data the best.

For the volume of scaled wood, six stepwise regressions were preformed. The first two included all 18 sites and used volume of wood scaled and the transformed volume of wood scaled as the response variables. These first stepwise calculations had very low R^2 (e.g. 0.34 for scaled volume). Streams with bankfull widths < 3 m have been identified as headwater and functioning different from larger stream sizes (Hassan *et al.* 2005). Chen *et al*. (2006 and 2008) also found a statistical difference in the volume of wood in streams <3 m bankfull width. For these reasons, when analyzing the volume of scaled wood, the dataset was split into 8 streams <3 m and 10 streams >3 m bankfull width. The stepwise regression was re-calculated at each stream size for both the scaled volume and the transformed scaled volume of wood.

Once the stepwise regressions were completed and the best predictor variables were identified, several multiple linear regressions (MLR) were calculated for the transformed and untransformed abundance and volume of LWD. The strength of the model was determined based on three characteristics:

1. The R^2-adjusted value
2. The significance of all of the predictor variables
3. The normality, linearity and equal variance of the residuals

4.3 RESULTS

4.3.1 DIAMETER CLASS DISTRIBUTION

The riparian zone when divided by forest type (Fig 4.2a) or stream size (Fig 4.2b) generally had a decreasing frequency with increasing diameter. The median diameter for all sites ranged from 0.05-0.1 m. The range in diameters was larger in the spruce forest, with one site (site 18) having trees up to 1 m in diameter; however, this was not reflected in the rest of the sites within that forest type. The pattern in small streams corresponded with the pattern observed in the pine-spruce forest sites. This reflected the fact that eight of the nine study sites in the pine-spruce forest were classified as small. The spruce forest had a similar trend as medium streams. This reflected the fact that six of the nine sites classified as medium were in the spruce forest. There was no difference in the diameter class distribution of the riparian forest when it was classified by forest type or stream size.

The LWD in small streams appeared to have less transport or organization than either the transitional and medium stream due to the higher frequency of lower diameter classes in small streams (Fig 4.2a-d). When LWD distribution was classified by forest type (4.2c) and stream size (4.2d), the diameter class distribution was different from the riparian zone distribution (Fig 4.2 a-b)). Streams classified as small had a peak at 0.1 m diameter and had a higher relative frequency for 0.05 m that either transitional or medium streams. Higher frequencies of smaller pieces are retained in the smaller streams. This could be a measurement bias because the smaller pieces may have not been recorded or measured in the larger streams if they were wedged or buried under larger pieces.

The diameter class distribution of both riparian forest and LWD did not visually appear different across forest type (Fig 4.2a-b) or stream size (Fig 4.2c-d). However, the distribution of LWD (Fig 4.2 c/d) was different than that in the riparian forest (4.2 a/b). Furthermore, this difference was larger in the transitional and medium streams. The difference in pattern suggests that at least some organization of wood is occurring due to within-stream transport and organization within the stream, with more occurring in transitional and medium streams.

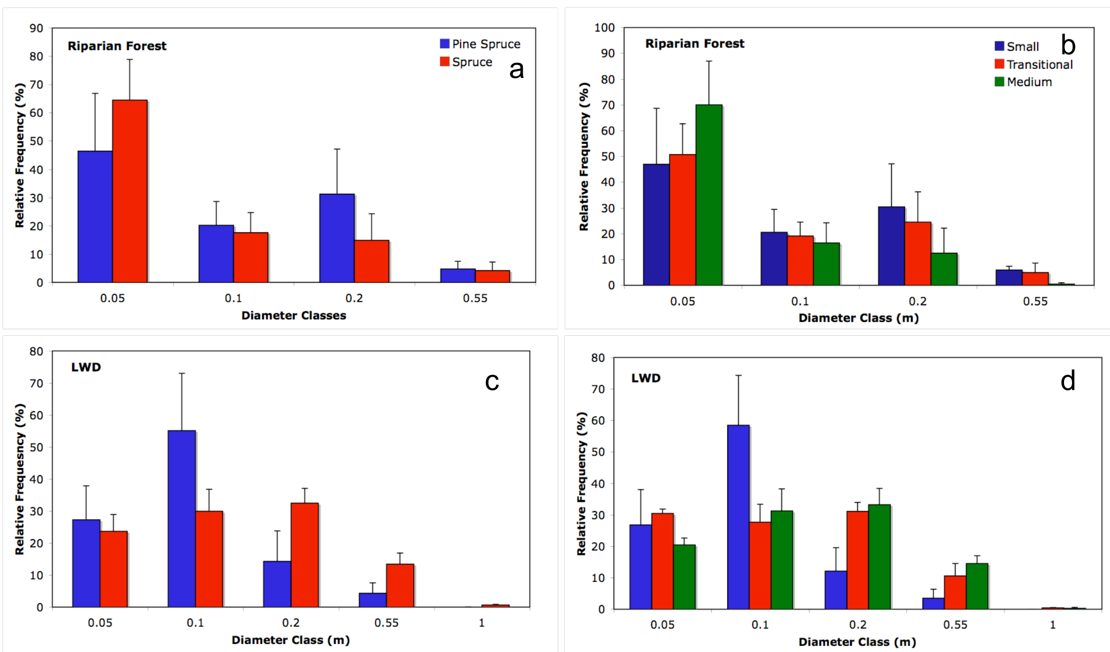


Fig 4.2 Mean frequency of diameter classes (bars) and standard deviation (lines) measured in the riparian forest and LWD. The means are presented by forest type (Left column: pine-spruce and spruce) and stream size (Right column: small, transitional and medium) in order to explore the trends in the data and identify riparian-controlled and stream-controlled categories.

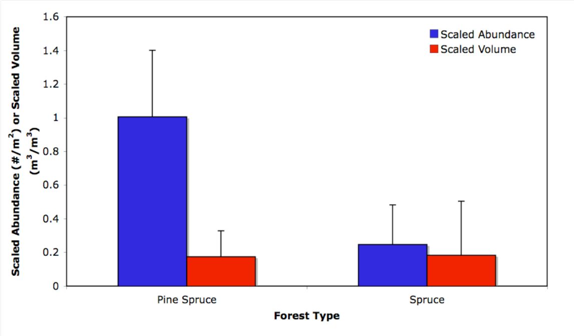
4.3.2 RIPARIAN AND STREAM CHARACTERISTICS

The first set of GLM compared the riparian forest characteristics between the two forest types. For the riparian forest characteristics, species composition measures were generally statistically significant between forest types, but structural characteristics were not different (Table 4.1). The importance values for Douglas-fir and lodge pole pine were significantly higher in the pine-spruce forest than in the spruce forest type. In contrast, the importance value for spruce was significantly lower in the pine-spruce forest than the spruce forest (Table 4.1), but differences were not significant for deciduous trees (at alpha 0.05). However, the spruce forest had a higher value than the pine-spruce forest at alpha of 0.1. These four groups represent 100% of the species composition in fourteen study sites and >90% of the species composition in the remaining sites (Appendix D: Fig D.1). The Simpson's biodiversity index, and the Shannon H1 had higher values in the spruce forest than in the pine-spruce forest.

The second set of GLM compared stream characteristics across stream size. The physical characteristics of the streams were significantly different across stream size (Table 4.1). As expected, the bankfull depth and width increased with stream size, while the slope and D_{95} decreased. The proportion of the stream reach measured along the thalweg that was associated with pools decreased with increasing stream size, while the proportion of riffles increased. The elevation of individual pools decreased with increasing stream size. The proportion of elevation change associated with riffles increased with stream size.

The final set of GLM compared abundance and volume of LWD across stream size and forest type. Stream size explained more variability in LWD abundance and volume than forest type (Table 4.2). Both stream size and forest type were significant in explaining the variability in the abundance of wood. The division by stream size, however, had a higher R^2 (0.84) and met the assumptions of ANOVA better than that by forest type (R^2 0.66) (Table 4.2). The mean values for all three stream sizes were significantly different from each other and decreased with stream size (Fig 4.3). For forest type, the mean value for the pine-spruce was significantly higher than for the spruce.

Stream size explained the variability in the volume of wood (P-value of 0.07 and R^2 of 0.29) better than forest type (Table 4.2, Fig 4.3). Forest type had no correlation to LWD volume. For stream size, the mean in transitional streams was significantly higher than the mean in medium streams (Fig 4.3). The mean for small streams was not significantly different from either stream size.



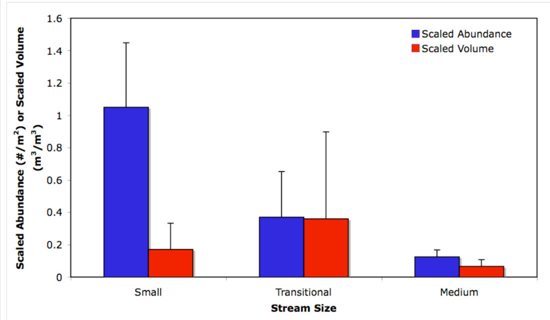


Fig 4.3 The mean values (bars) and standard deviation (lines) for scaled abundance and volume of LWD grouped by forest type and stream size.

Table 4.1 Results from the riparian and stream characteristic general linear models.

Variable	**P-value**
Forest Composition	
Importance Values	
Douglas-fir importance value	0.0005
Lodge pole pine importance value	0.04
Spruce importance value	0.001
Deciduous trees importance value	0.07
Biodiversity Indexes	
Simpson's Diversity	0.007
Shannon H1	0.01
Forest Structure	
Mean basal area per stem	0.79
Basal area per hectare	0.52
Stems per hectare	0.41
Stream Characteristics	
Bankfull width (m)	0.0001
Bankfull depth (m)	0.013
Slope (m/m)	0.01
D_{95} (mm)	0.0054
Morphologic Unit	
Distance-pool	0.05
Distance-riffle	0.09
Elevation-pool	0.05
Elevation-riffle	0.02

Table 4.2 Results from the stream size and forest type Analysis of Variance. * indicated the stronger model that met all of the assumptions of ANOVA.

Class	Model	R^2	Grouping
Abundance (#/m^2)			
Stream Size	<0.0001	0.84*	small (A) >transitional (B)>medium(C)
Forest Type	<0.0001	0.66	pine (A) > spruce (B)
Volume (m^3/m^3)			
Stream Size	0.07	0.29*	medium (A)<transitional (B) Small (AB) equals both medium and transitional
Forest Type	0.46	0.03	pine (A)= spruce (A)

4.3.3 PREDICTOR REGRESSION MODELS FOR THE ABUNDANCE AND VOLUME OF SCALED WOOD

4.3.3.1 STEPWISE SELECTION TOOL

The stepwise selection tool identified stream characteristics as important for estimating the abundance of wood. For the volume of wood, physical stream characteristics were also identified as important; however, the relations developed by the stepwise tool were poor. When scaled volume was divided into streams < 3 m and > 3 m wide, the stepwise tool developed stronger models. In streams < 3 m wide, riparian forest characteristics were identified as more important than stream characteristics. For streams > 3 m wide, stream characteristics were identified as more important than forest characteristics.

Both the transformed (Log_{10}) and untransformed abundance of scaled wood were used as the response variable to determine which models produced higher correlations and what values were similar for each equation. For both equations the first two variables included in the models were $\log_{10}$ bankfull width (m) and slope (Table 4.3). These two variables produced an R^2 of 0.79 for the abundance of wood and 0.93 for the transformed abundance. The stepwise procedure for the abundance of scaled wood included six variables, four of which were physical stream characteristics (R^2 = 0.91; Table 4.3). The stepwise procedure for the transformed abundance of wood included five variables, three of which were stream characteristics (Table 4.3). For both the transformed and untransformed response variable, the R^2 value was high before the two riparian characteristics were included in the model.

Predicting the transformed (Log_{10}) and untransformed volume of scaled wood had poor stepwise equations (Table 4.3). The untransformed volume of scaled wood included two variables, bankfull depth (m) and D_{95} (mm), but had a relatively low R^2 (R^2 =0.34). The transformed volume also included two variables, bankfull width and the importance value of lodgepole pine (R^2 = 0.47).

Dividing the dataset into streams < 3 m versus > 3 m wide improved the R^2 values calculated by the stepwise procedure (Table 4.4). For streams < 3 m wide, no variables met the criteria of having a P-value ≥ 0.15 when the volume of scaled wood was the response variable. The model for the transformed volume of scaled wood, however, included six variables including a variety of riparian forest and stream characteristics (Table 4.4). In streams > 3 m wide, the model for the volume of scaled wood included seven variables and the model for the transformed volume included eight variables (Table 4.5). Both models contained physical stream characteristics as well as riparian forest characteristics. The Log_{10} of bankfull depth was the first variable included in both equations and produced an R^2 of 0.88 for Log_{10} scaled volume and 0.83 for predicting scaled volume.

Table 4.3 Results from stepwise regression including all 18

Step	Variable	Parameter Estimate	R^2
Abundance			
Log_{10} Abundance (#/m^2)			
1	*Log_{10}* bankfull width (m)	-0.99	0.89
2	Slope (m/m)	7.5	0.93
3	*Log_{10}* distance-glide (%)	-0.22	0.95
4	Importance value for Douglas-fir (%)	0.0009	0.97
5	Simpson Diversity	0.27	0.98
Abundance (#/m^2)			
1	*Log_{10}* bankfull width (m)	-2.54	0.70
2	Slope (m/m)	38.19	0.79
3	*Log_{10}* slope (m/m)	-1.69	0.88
4	Bankfull width (m)	1.13	0.91
5	Shannon H1	0.38	0.93
6	*Log_{10}* D_{95} (mm)	-0.33	0.96
Volume			
Log_{10} Volume (m^3/m^3)			
1	Bankfull width (m)	-0.08	0.28
2	Importance value for lodgepole pine (%)	-0.003	0.47
Volume (m^3/m^3)			
1	Bankfull depth (m)	-1.05	0.17
2	*Log_{10}* D_{95} (mm)	0.41	0.34

Table 4.4 The results from the stepwise regression for volume divided into stream size according the patterns observed in the dataset.

Step	Variable	Parameter Estimate	R^2
Small streams (bankfull width <3 m)			
Log_{10} Volume (m^3/m^3)			
1	*Log_{10}* importance value of Douglas-fir (%)	2.12	0.36
2	*Log_{10}* bankfull width (m)	-6.54	0.65
3	Simpons Diversity Index	-7.64	0.86
4	Shannon H1	3.36	0.98
5	Slope (m/m)	-3.51	0.99
6	*Log_{10}* bankfull depth (m)	0.17	1.0
Volume (m^3/m^3)			
No variables met the criteria for a stepwise selection			
Medium/Transition streams (bankfull width >3 m)			
Log_{10} Volume (m^3/m^3)			
1	*Log_{10}* bankfull depth (m)	-2.39	0.88
2	*Log_{10}* distance-pool	-0.52	0.95
3	Shannon H1	0.46	0.98
4	*Log_{10}* distance-glide	0.25	0.993
5	*Log_{10}* Importance value Douglas-fir	0.06	0.997
6	*Log_{10}* elevation-pool	0.36	0.9995
7	Basal area per hectare (m^2/ha)	-0.07	0.9999
8	*Log_{10}* Basal area per hectare (m^2/ha)	-0.00000004	1.0
Volume (m^3/m^3)			
1	*Log_{10}* bankfull depth (m)	-9.14	0.83
2	Bankfull depth (m)	4.17	0.97
3	*Log_{10}* D_{95} (mm)	1.48	0.99
4	D_{95} (mm)	-0.003	1.0
5	Slope (m/m)	0.44	1.0
6	*Log_{10}* importance value of Douglas-fir	0.003	1.0
7	Basal area per hectare (m^2/ha)	-0.000000004	1.0

4.3.3.2 Predictor models for the abundance and volume of LWD

Stream characteristics produced the best predictor model for the abundance of scaled wood. Riparian and stream characteristics were used to produced the best predictor model for the volume of scaled wood in streams < 3 m wide. The volume of scaled wood in streams > 3 m wide was predicted by stream characteristics. Models were run for every step that the step-wise selector had identified for predicting both the Log_{10} and scaled abundance and models and one model for each predictor variable had significant model, intercept and parameter values as well as met the assumptions of normality, linearity and equal variance of the residuals (Appendix E).

To determine the best equation for the abundance of scaled wood, a model was run to represent each step of the stepwise procedure. The initial two regressions included all of the parameters in the total stepwise selection procedure for both transformed and untransformed abundance of scaled wood (Table 4.5). For both models, no parameters were significant (Table 4.5). The only model that had all parameters significant for both transformed and untransformed abundance used only Log_{10} bankfull width as the predictor variable. The R^2 for Log_{10} abundance was 0.92 and for abundance was 0.76. Even though the abundance R^2 was lower than Log_{10} abundance, I would suggest that the abundance equation be used for predicting the abundance of LWD as it is preferable to use untransformed y-variables in equations.

Two equations were identified as the best for predicting the volume of scaled wood (Table 4.4 and 4.5). One equation was for streams < 3 m wide and the other was for streams > 3 m wide. For streams < 3 m wide, multiple equations were attempted. The best model had six parameters, three were riparian and three were stream parameters. The variable that explained the most variability in the dataset was the importance value for the Douglas-fir, which was the most common coniferous tree in the riparian forest. Six parameters developed from a sample size of 18 sites may be over-parametization and there was multicollinearity between predictor variables and between the response and the predictor variables in the calculated equation, which may inflate the R^2 (Kutner *et al.* 2005). The biodiversity indexes were similar measures that had a linear relationship. The response variable was scaled by unit stream volume, which was calculated as the length of the survey multiplied by the bankfull width and the bankfull depth. Since bankfull width was added to the equation in the second step, this variable could have had collinearity with the response variable. The variety and number of parameters, as well as the difficulty in producing a significant model with fewer parameters suggests that predicting the volume in streams < 3 m wide is difficult and may be inappropriate.

For streams with bankfull width > 3 m, several models were developed (Table 4.5). Two regression models were developed that included all of the parameters produced by the stepwise procedure (Table 4.5). Both models had high R^2 values; however, each had multiple parameters that were not significant (Table 4.5). Only one model met the assumptions, had a high R^2, and all parameters were significant (Table 4.5). This model predicted the scaled volume of wood using Log_{10} bankfull depth and the bankfull depth

Table 4.5 Results from regression models calculated based on the stepwise regression. The best model for number and volume are indicated by **. P-values are included to support reason for choosing the best model.

Model Parameter	**Parameter Estimate**	**P-value**
Scaled Abundance		
Model 1 Log_{10} Abundance (#/m^2) R^2 = 0.89		
Model	N/A	0.003
Intercept	0.01	0.77
Log_{10} bankfull width (m)	-1.03	0.59
Slope (m/m)	7.66	0.32
Log_{10} distance-glide	-1.74	0.52
Importance value of Douglas-fir (%)	0.0009	0.42
Model 2 Log_{10} Abundance (#/m^2) R^2 = 0.92		
Model	N/A	<0.0001
Intercept	0.50	0.0039
Log_{10} bankfull width (m)	-1.48	<0.0001
Model 3 Abundance (#/m^2) R^2 = 0.89		
Model	N/A	0.02
Intercept	-0.56	0.68
Log_{10} bankfull width (m)	-1.94	0.08
Slope (m/m)	28.58	0.10
Log_{10} slope (m/m)	-1.21	0.11
Bankful width (m)	0.08	0.16
Shannon H1	0.05	0.77
Log_{10} D_{95} (mm)	-0.46	0.12
*Model 4 Abundance (#/m^2) R^2 = 0.76***		
Model	N/A	0.0006
Intercept	1.06	<0.0001
Log_{10} bankfull width (m)	-0.96	0.0006
Scaled Volume - bankfull width > 3 m		
Model 1 Log_{10} Volume (m^3/m^3) R^2 = 0.99		
Model	N/A	0.06
Intercept	-2.37	0.25
Bankfull depth (m)	-3.32	0.03
Distance-pool (%)	-0.35	0.35
Shannon H1	0.55	0.11
Log_{10} distance-glide	0.25	0.32
Log_{10} Importance value Douglas-fir	0.11	0.14
Log_{10} elevation-pool	1.76	0.38
Basal area per hectare (m^2/ha)	0.06	0.70
Log_{10} Basal area per hectare (m^2/ha)	-0.00000009	0.69
*Model 2 Log_{10} Volume (m^3/m^3) R^2 = 0.88***		
Model	N/A	<0.0001
Intercept	0.95	0.006
Bankfull depth (m)	-2.46	<0.0001

Model Parameter	Parameter Estimate	P-Value
Model 3 Volume (m^3/m^3) R^2 = 0.92		
Model	N/A	0.06
Intercept	-5.57	0.30
Log_{10} bankfull depth (m)	-12.93	0.14
Bankfull depth (m)	7.10	0.19
Log_{10} D_{95} (mm)	-0.90	0.79
D_{95} (mm)	0.003	0.75
Slope (m/m)	1.10	0.87
Log_{10} importance value of Douglas-fir	0.08	0.35
Basal area per hectare (m^2/ha)	0.00000002	0.94
Model 4 Log_{10} Volume (m^3/m^3) R^2 = 0.95		
Model	N/A	<0.0001
Intercept	-4.72	0.0015
Log_{10} bankfull depth (m)	-9.75	0.0003
Bankfull depth (m)	4.8	0.0017
Scaled Volume - bankfull width < 3 m		
*Model 1 Log_{10} Volume (m^3/m^3) R^2 =1.0***		
Model	N/A	0.0001
Intercept	-2.8	0.0004
Log_{10} Douglas-fir importance value (%)	2.12	0.0003
Log_{10} bankfull width (m)	-6.54	0.0003
Simpson's Diversity	-7.64	0.0012
Shannon H1	3.36	0.0015
Slope (m/m)	-3.51	0.0021
Log_{10} bankfull depth (m)	0.17	0.0095

4.4 Discussion

This chapter has focused on analyzing the differences in the riparian forest and stream characteristics across the 18 field sites in order to determine if wood characteristics were mainly riparian-controlled or stream-controlled. Also, this chapter proposed predictive models for abundance and volume of LWD based on riparian forest and/or stream characteristics. The discussion will critically look at the results in order to put into context of current literature (1) the distribution of riparian forest and LWD size classes, (2) the riparian forest and stream characteristics used in the predictive models, and (3) the patterns produced by the predictive models for both volume and abundance over multiple stream sizes.

4.4.1 Comparison of the Riparian Forest and LWD

LWD piece size is important because (1) it dictates the depth of flow necessary to initiate movement and (2) controls if wood is likely to become jammed or lodged within the channel, increasing its stability (Baudrick and Grant 2000, Gurnell *et al*. 2002).

Comparing the LWD distribution to the riparian forest distribution can provide an indication of the level of transport within a stream. The LWD distribution for the 18 field sites differed from riparian distribution with increasing stream size. This suggests that transport and reorganization within the stream may become more important with increasing stream size.

The LWD diameter class size distribution was consistent with literature for field sites in the southern Interior of BC and in western Washington (Chen *et al.* 2006; Jackson and Sturm 2002). Jackson and Sturm (2002) studied 41 field sites including streams with bankfull width < 3 m. For these sites, the 10-20 cm diameter pieces represented the highest proportion of the diameter classes, which is similar to small streams observed in this study (< 3 m bankfull flow width) in Fig 4.2 d. Chen *et al.* (2006) reported a decrease in the proportion of wood <15 cm diameter and an increase in all other diameter size classes up to >30 cm with increasing stream size. This pattern was also observed in the Interior of BC dataset with the medium streams (bankfull width> 5 m) having the highest proportion of large pieces of wood. Gurnell *et al*. (2002) reported that LWD reached its maximum average piece size in medium rivers due to the inability of stream to transport pieces a great distance from the source and the size of pieces relative to the bankfull width of the channel. In order to see if this is true for the Interior of BC, additional data would need to be collected at streams larger than the field sites used in this study. Within the data of this study, however; the LWD size follows the pattern of increasing with stream size.

LWD recruitment models include information about the riparian forest, LWD within the stream, and mechanisms of LWD recruitment into the stream, which can be difficult to determine due to decay of logs or transport from their original deposition environment (e.g. Martin and Benda 2001). Transport of wood is both poorly understood and difficult to quantify; therefore, it not explicitly modeled but is often assumed to be part of the decay function in models (e.g. Murphy and Koski 1989). For the 18 field sites in this study, the distribution of LWD size classes across stream size was different (Fig 4.2 d). The difference in distribution of LWD at different stream sizes within the field sites suggests wood transport and could be use to calibrate transport functions in LWD recruitment models.

4.4.2 Analysis of characteristics used to predict LWD

Physical stream characteristics were determined to be more important than riparian forest characteristics for predicting abundance and volume of LWD. This finding is consistent with the way LWD is represented in the literature as a function of stream size and not a function of forest structure. LWD loading is often plotted against bankfull width, stream power, or drainage area to show the relation between loading and stream characteristics (e.g. Gurnell 2003, Hassan *et al.* 2005). These plots produce power-law relations with a negative slope: as stream size increases the LWD loading decreases. I am not aware of any literature that plotted LWD against a continuous forest structure measure such as stems per hectare. Some studies have stratified their sites according to riparian forest disturbance history or age; however, the results for LWD loading were plotted against physical stream characteristics (e.g. Gurnell 2003, McHenry *et al.* 1998).

Slope and bankfull width were more important than riparian characteristics for predicting the abundance of scaled wood. Riparian characteristics added little additional strength to the statistical model. This suggested that adding riparian characteristics might over-parameterize the model for predicting the abundance of wood. Jackson and Sturm (2002) used stepwise regressions to explore the relative importance of geomorphic variables and found physical stream characteristics to be linked to LWD loading. Since the physical characteristics of the riparian zones were not significantly different for the 18 field sites but the physical characteristics of the streams were different, stream characteristics more likely affected LWD abundance. This interpretation is consistent with the findings of May and Gresswell (2002).

For streams with bankfull width < 3 m, riparian characteristics were more important than stream characteristics for the prediction of LWD volume. The three of the four model parameters were riparian characteristics: the importance value of Douglas-fir, the bankfull width, Simpson's diversity index and the Shannon H1 diversity index. The mobility of LWD increases with channel width, causing fluvial reorganization of wood in streams (Benda and Martin 2001). May and Gresswell (2003) reported that in small streams, 16% of the wood was less then the mean bankfull width and only 1% of this was transported downstream. Additionally, May and Gresswell (2003) reported that, in small streams with bankfull width < 5 m, 63% of the pieces of LWD recruited from the hillslope or local riparian area. Moreover, the size of the wood and the distance of transport from source are dependent on stream size. The smaller streams in this study would have a lower transport capacity and the diameter distribution of LWD reflects the riparian forest more closely. These findings are consistent with May and Gresswell (2003) and may explain why riparian characteristics were important in the equation. The predictive model; however, was over-paramatized and had a very high R^2-value of 1.0. This may suggest that due to low degree of variability among the streams < 3 m wide that were used to develop this model. Therefore, application of this model to predict LWD volume in other streams should be constrained to similar small streams and riparian forests.

For streams with bankfull width > 3 m, the physical stream characteristic that contributed the most to the strength of the equation was bankfull flow depth. Baurerick and Grant (2000) found mobility of wood to be linked to the bankfull flow depth more than the width. In this study, streams > 3 m wide showed reorganization within the stream and transport downstream. Since Bauderick and Grant (2000) linked mobility with depth, it is logical that in sites considered stream-controlled, that bankfull depth would be a sensitive parameter for understanding the volume of wood. Hygelund and Manga (2003) reported that when LWD diameter was ≥30% of the depth, LWD was no longer affected by the local velocity increase due to the obstruction (LWD) but instead by the depth average velocity, which is lower than the local velocity as it is calculated over the profile of the water column. This finding may be why (1) bankfull depth was the predictive variable in the volume equation, and (2) the piece size increased with stream size. Smaller pieces of wood would be more easily mobilized in larger streams.

4.4.3 Patterns in LWD predictive models for abundance and volume

Physical stream characteristics produced a better-fit model than riparian forest characteristics for the 18 field sites (Table 4.6). This result suggests that these sites are more stream-controlled with no significant structural differences in the forest types (Table 4.2, 4.4, 4.5). The results also showed a decrease in abundance with increasing stream size and an increase in volume until approximately a 5 m-bankfull width, at which point the volume decreased with increasing bankfull width (Fig 4.3 a-b). Data values for abundance and volume measures from current literature were standardized to scale by unit area and stratified by forest type in order to explore: (1) the pattern in the abundance and volume of LWD across stream size and (2) the effect of forest type and stream size at multiple forest types (Fig 4.4 a-b).

The following section will compare the Interior of BC dataset and the Hinton, Alberta dataset with the published literature. All datasets were collected in old growth forests with no disturbance. All research used a diameter measure of ≤10 cm, with on of the research papers using ≤8 cm (Jones and Daniels 2008), and a length parameter of ≤1 m, with one paper using ≤0.5 m (Gomi *et al*. 2001) and one using ≤ 3 m (Richmond and Fausch 1995). Four field sites had bankfull widths ≥20 m. These sights were eliminated from the dataset in order to (1) allow for a more direct comparison with the 18 field sites in this thesis and (2) observe in detail the differences between forest type. For the abundance plot with all field sites please refer to Appendix G. The data were grouped based on (1) location and (2) dominant tree species as described in the methods section of each paper. The only data not grouped in this was 'Interior BC' and represents with 18 field sites which consist of spruce and pine-spruce sites that have different species composition, but are not structurally different (Table 4.2). LWD volume has a stronger relationship to bankfull depth (Chen *et al.* 2006); however, because few papers report the bankfull depth and most report bankfull width, both abundance and volume have been presented as a function of bankfull width.

The pattern in abundance of LWD observed in the Interior of BC is consistent across all forest types; however, the exact values stratify over forest type with increases in stream size (Fig 4.4 a). The hemlock-fir-cedar forest had generally lower abundance than the Interior of BC across all three stream sizes. The spruce-fir and the pine-spruce had similar values, though slightly lower, than the Interior of BC. This reflects the fact that the dataset from the Interior of BC is composed of spruce and pine-spruce forests with similar species composition to the spruce-fir and pine-spruce forests. The spruce- alder forest is only represented in the transitional and medium streams; however, it has a decreasing pattern and lower values than the Interior of BC. The differences in LWD abundance between forest types increased with increasing stream size. Fig 4.4a suggests comparisons or predictive models should be stratified by forests with different structure.

The patterns in the volume of LWD measured in the Interior of BC are similar to other forest types; however, the values are somewhat different across forest type. Fewer studies reported volume of LWD; as a result, the different forest types are not as well represented across a variety of bankfull widths. Generally, the LWD volume shows a slight decrease with increasing stream size with the most variability in streams with bankfull width ≤ 3 m. The values reported for the spruce-alder forest are the lowest and represent the narrowest range of bankfull widths. Fig 4.4b suggests that comparisons or predictive models should be stratified by forests with different structures.

When considering abundance and volume of LWD, variation in piece size can be generally observed across different forest types, adding to the argument that forest types of different structure should be stratified if used for comparison or predictive models. Generally, the pine-spruce and the spruce-fir forests have a similar pattern as the Interior of BC dataset: high abundance that decreases with stream size and a slight decrease in volume with stream size. In hemlock-fir-cedar forests, there is generally low abundance and high volume. This suggests that compared to the pine-spruce or the spruce-fir forest, the hemlock-fir-cedar forest would have a fewer number of larger pieces of LWD. The spruce-alder forest had low abundance and the lowest volume suggesting a fewer number of pieces than other forest types and that these pieces were smaller than other forest types. These results suggest that because the forest structure can affect piece size, finding should be stratified by forest structure. This would allow the sites from the Interior of BC, the spruce-fir and the pine-spruce forest to be grouped together for a comparison.

Gurnell (2003) grouped LWD by four forest types in a meta-analysis of 152 sites from multiple studies different in storage of LWD: (1) Redwood, (2) Other Conifers, (3) Mixed Conifer and Hardwoods, and (4) Salicaceae. Group 3 (mixed conifers and hardwoods) is equivalent to Spruce-Alder, while the remainder of the categories would fall into what Gurnell (2003) classified as Group 2 (Other conifers). Gurnell (2003) showed group 3 had a significantly mean lower volume per hectare of LWD in streams than group 2, which is consistent with Fig 4.4 b. Gurnell (2003) plotted the sites against channel width, and for this graph group 3 plotted generally below group 2; however, the difference was not as pronounced as in Fig 4.4 b.

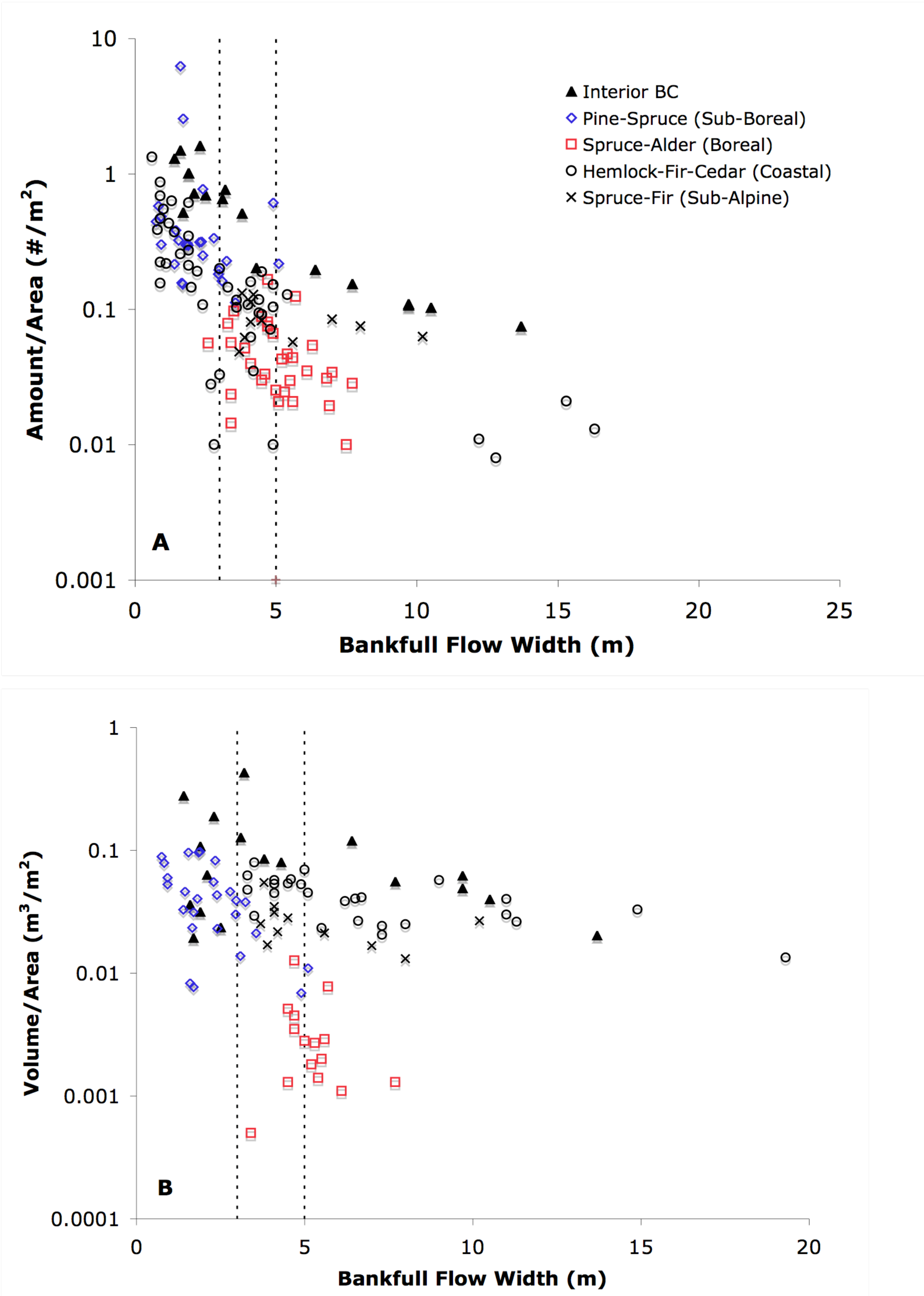


Fig 4.4 Comparison of LWD abundance (A) and volume (B) values in the literature to field site measurements (Interior BC). The categories were grouped by (1) location and (2) dominant tree species. The dashed lines represent the stream size categories (1) small is < 3 m bankfull flow width, (2) transitional is 3-5 m and (3) medium is > 5 m.

4.5 Major Findings and Research Implications

For the 18 field sites, stream size influences the LWD distribution more than forest type. This is because, even though the forest types differed in species composition, the forest structure was similar across all 18 sites. The streams, however, were different across stream sizes and categorizing by stream size produced a better model fit. The pattern in LWD abundance was a decrease with increasing stream size and for volume LWD increased to the transitional stream size then decreased. This pattern was also observed in the predictive model. The predictive models for abundance and volume focused on stream characteristics more than the riparian forest. Models of LWD abundance produced a stronger equation that could be applied over all stream sizes, whereas volume could only be predicted in streams with bankfull width ≥ 3 m because the model for streams ≤ 3 m wide was over-parameterized.

In the context of multiple studies from multiple study regions, LWD abundance and volume generally had the same pattern within forest type, however; the values were stratified by forest type. These findings are similar to Gurnell (2003) and suggests that if forest structure is different then comparisons across studies should be stratified by forest type.

5 PATTERNS IN THE SPATIAL DISTRIBUTION OF LARGE WOODY DEBRIS

5.1 INTRODUCTION

Understanding the distribution, dynamics and function of LWD through a channel network is necessary for understanding wood dynamics at the watershed scale (Chen *et al.* 2006*)*. Research on LWD has focused at the reach scale, often in medium size channels; however, to understand wood dynamic in the watershed it is important to study across wide range of stream sizes and morphology (Hassan *et al.* 2005, Chen *et al.* 2006). The goal of this chapter is to examine patterns in LWD abundance, volume and size for jam, position and orientation classes within the stream at each of the 18 field sites. Three questions guided the research:

1. Are there spatial patterns in the abundance and volume of LWD?
2. Do these patterns change with stream size?
3. Does free and jammed wood have the same or different patterns?

Three major controls on the function of LWD are: (1) position of the LWD relative to the streambed, (2) orientation of the LWD relative to stream flow, and (3) the size of the pieces relative to channel parameters. This chapter will focus on the position and orientation categories and the interaction of these categories with stream size and jam classes. Size of wood will be incorporated into the results and discussion as it relates to the other class variables.

Additionally, this study will compare the pattern for free and jammed wood, a topic neglected within the literature. LWD jams effect stream morphology and hydrology as well as the surrounding riparian forest (e.g. Hogan 1985, Abbe and Montgomery (2003). These effects have been reported for streams in coastal forests such as the Queen Charlotte Islands (Hogan 1985), Vancouver Island (Haschenburger and Rice 2004) and the Oregon Coast Range (Montgomery *et al.* 2003). Kreutzweiser *et al.* (2005), however, reported that in the boreal forest, jams were small relative to other forest types and contributed little to sediment retention and storage. The study sites in the Interior of BC have riparian forests compositions that are different from either the coastal range or the boreal forest, for this reason jam class distribution of abundance and volume was a key variable to examine in this study.

LWD is variable across space and time (Gurnell 2003). By reporting on 18 field sites over a range of three stream sizes (small, transitional and medium), the natural variability and patterns observed should be reflective of the true patterns within the Northern Interior of BC These results will be put into context by comparing values and patterns to those reported on in various forest types around the world within the discussion section.

5.2 Methods

5.2.1 Definition of the parameters and terminology

Both abundance and volume of LWD are presented in this chapter. The parameters used to define LWD were 0.1 m and 0.5 m in diameter and length, respectively (for definition justification see Chapter 3). Abundance and volume are the total number of pieces and total volume of wood located at a site. Both abundance and volume measures were scaled by unit area of stream. Values were analyzed and presented as both scaled and relative; relative was reported as percentage associated with a particular category or combination of categories at an individual stream size. The relative abundance and volume of wood in each category (i/ii/iii) was calculated as the proportion of total wood found in each stream size.

In order to explore the spatial patterns in the abundance and volume, the LWD was grouped into four categories: (1) stream size, (2) orientation, (3) position and (4) jam (Table 5.1). Each category had a specific number of classes associated with it ranging from two to three (see chapter 2 for data collection and calculations). Combinations of these categories and classes were used to produce summary tables that increased in complexity with the increasing number of classes (Table 5.2). The summary tables contained information about the absolute abundance and volume of wood measured at each site within a specific class or combination of classes (Appendix E: Example of summary table number two).

Table 5.1 Descriptions of the categorical variables used to summarize the patterns in LWD.

Category Name	Number of Classes	Class Descriptions
Stream Size	3	Based on stream bankfull width: 1. Small: < 3 m 2. Transitional: 3-5 m 3. Medium: > 5 m
Orientation	3	Relative to stream flow: 1. Parallel (II)* 2. Perpendicular (T) 3. Diagonal upstream (/)
Position	3	Interaction with streambed: 1. Bridged above the bed 2. Half in the bed 3. Fully in the bed
Jam	2	Location in the stream: 1. In a LWD jam 2. Free in the stream

*Symbols in brackets represent abbreviations used for orientation classes in figures throughout this chapter

Table 5.2 List of summary tables calculated using SAS 9.1. All four were calculated for the absolute abundance and volume of wood. This table lists the summary tables and the total possible class combinations. The total number of combinations increases with increasing numbers of class variables.

Table	**Categories**	**Number of Class Combinations**
1	Stream Size	3
2	Stream Size*Jam	6
3	Stream Size*Jam*Position	18
4	Stream Size*Jam*Orientation	18

5.2.2 Spatial patterns in LWD abundance and volume

Spatial patterns in LWD relative abundance and relative volume were explored using both descriptive and statistical methods. Patterns were explored for both wood abundance and volume using absolute and relative data. The wood diameter and length distributions were also analyzed.

The scaled volume and abundance for each study site were plotted against bankfull width. Plots were produced for all of the class combinations of stream size and jam class with the orientation and position classes. These plots were used to explore variation in the data with increases in bankfull width. General linear models (GLM) were used to determine if the absolute scaled volume and abundance of wood varied with stream size, position, orientation, and jam classes. A series of GLM's were calculated for each class variable combination and the results were compared across stream sizes. The initial set of GLM's was calculated for the scaled variables, while the second set was developed for patterns in jam classes and included jam, position, and orientation. For example, the orientation of the parallel wood in small streams was compared to:

1. Perpendicular and diagonal wood in small streams
2. Parallel wood in transitional and medium streams

The alpha value of 0.05 was used for significant results. If interactions were significant in the GLM's, then the individual correlations between the categories had to be analyzed. This involved identifying the number of correlations possible with the interaction term and dividing alpha by this number to reduce the inflation of the alpha term (Table 5.3). The non-inflated alpha values were used to examine the least square means output and identify significance between stream size and classes.

Table 5.3 The GLM's number of correlations and alpha values to explore the trends in LWD. The number of correlations indicated for are for the maximum interaction term for each GLM. The alpha value was divided by the number of correlations in order to reduce the inflation of alpha.

GLM	Class Variables	Number of Correlations	Alpha 0.05	Alpha 0.1
1	Stream Size	3	0.017	0.03
2	Stream Size*Jam	15	0.003	0.007
3	Stream Size*Jam*Orientation	153	0.0003	0.0006
4	Stream Size*Jam*Position	153	0.0003	0.0006

5.2.3 CHARACTERISTICS OF LWD JAM

Several characteristics of the LWD jams were recorded in the field. From these variables, the average jam frequency (#/100m^2) and length (m) was calculated over the three stream size categories. This was done to (1) observe the relationship between jam characteristics and stream size and (2) give context to abundance and volume measures within jam classes. The mean and median jam length was calculated across jam class for all three stream sizes. The distribution of jam lengths is also presented as a histogram classified by 2 m length increments. This was done to describe the distribution of LWD at multiple streams sizes. The jam frequency is presented as number of jams per 100 m^2. The jam frequency was first calculated for each of the 18 field sites and the sites were then classified by stream size and the mean was calculated. GLM were used to determine if the mean jam length and jam frequency were different across stream size classes. In order to avoid the inflation of the alpha-value of 0.05, p-values were divided by 3 when comparing the three correlations produced for each GLM.

5.3 Results

Due to the number of class combinations, the patterns have been discussed for the abundance and volume of LWD. The statistical significance for each class combination is not stated in the text but has been identified in tables that accompany each section. In these tables, the numbers indicated significant groupings within classes across stream size and the letters indicated significant groupings within stream size across classes.

5.3.1 Overall pattern in LWD

The scaled abundance and volume of LWD was significantly affected by stream size (Fig 5.1, Table 5.4). Wood abundance decreased with increasing stream size for all three means (P-value 0.0001) (Fig 5.1, Table 5.4). When the LWD was plotted against bankfull width, the abundance decreased with increased stream size (Fig 5.1). The volume of wood increased from small to transitional streams and then decreased to medium streams (Fig 5.1, Table 5.5). Transitional (0.36 m^3/m^3) streams had a significantly larger mean than medium (0.07 m^3/m^3) streams (Fig 5.1). Small (0.17 m^3/m^3) streams were not significantly different from either transitional or medium streams. When plotted against bankfull width, the variability in the volume of LWD decreased with increasing stream size (Fig 5.1). Small and transitional streams had a large range in values (0.03-0.48 m^3/m^3 and 0.09-1.4 m^3/m^3) for a small range in bankfull widths (< 3 m and 3-5 m). Medium streams had bankfull widths from 5 to 14 m and had volumes that ranged only from 0.02-0.14 m^3/m^3.

When comparing the patterns, small streams had the largest difference between the abundance and volume. For transitional and medium streams, the patterns in volume mimicked the abundance. These findings show that there were a higher number of low volume pieces in small streams than in either transitional or medium.

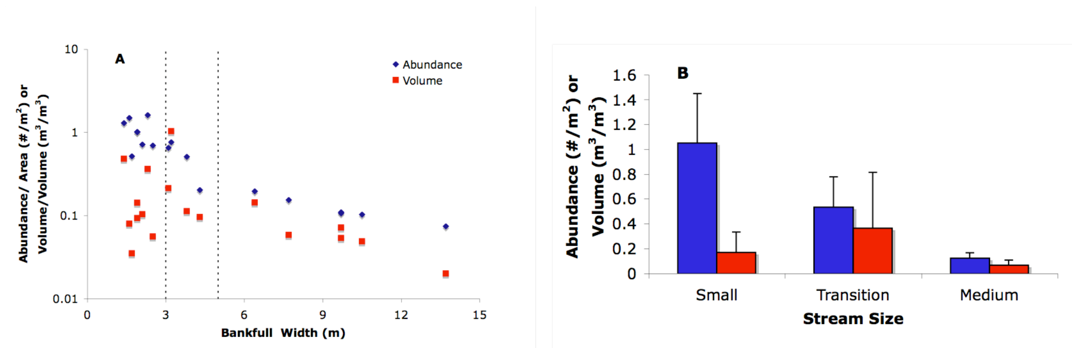


Fig 5.1 The pattern for LWD abundance and volume. Plot A represents individual stream values and Plot B represents the mean and standard deviation for each stream size. The dashed lines (A) represent the stream size category divisions that were based on Chen *et al.* (2006).

Table 5.4 The calculated mean for the abundance and volume at each stream size. The group identifies statistical significance. Statistically different means have different numbers.

Stream Size	Mean	Group
Scaled Abundance		
Small	1.05	1
Transitional	0.53	2
Medium	0.12	3
Scaled Volume		
Small	0.17	12
Transitional	0.36	1
Medium	0.07	2

5.3.2 Patterns in Jam Classes

The abundance and volume of wood in streams was different across jam classes and stream size (Fig 5.2). The pattern in free wood was similar to the overall results (Fig

5.1), while the pattern in jammed wood differed (Fig 5.2). The distribution of wood in diameter and length class was different across stream size and jam class (Fig 5.3).

The scaled and relative abundance of wood was affected by jam class and stream size. The scaled abundance of free LWD (not in a jam) decreased significantly with stream size, which was similar to the overall results (Fig 5.2 A). The scaled abundance of jammed wood decreased with stream size; however, only the mean value for medium streams (0.06 pieces/m^2) was significantly less than either small (0.29 pieces/m^2) or transitional (0.30 pieces/m^2) streams (Fig 5.2 A). Small streams had a significantly higher abundance of free wood than jammed wood for scaled abundance.

The scaled and relative volume of wood had a similar pattern to the overall results with a peak volume in transitional streams for both jammed and free wood (Fig 5.2 B). The mean scaled volume was not significant across stream size for either jammed or free wood. The relative volume of free wood in small streams was higher than the relative volume of jammed wood (Fig 5.2 D). The scaled volume of free wood in small streams was significantly higher than the jammed wood. For transitional and medium streams, approximately half of the wood in the streams was associated with jams. This suggested that as stream size increased, jams became more important to the morphology of the stream relative to the free wood in the stream.

The trends in abundance and volume of wood across stream size were different between jam classes. Free wood abundance and volume had similar results to the overall results: (1) small streams had high abundance and low volume, (2) transitional streams had moderate volume and abundance, and (3) medium streams had low volume and abundance. Jammed wood had different results: (1) small streams had moderate abundance and low volume, (2) transitional streams had moderate abundance and volume, and (3) medium streams had low abundance and volume. In small streams proportionally more of the wood was free in the stream and the size of pieces of free wood in the stream was smaller than wood in jams. This outcome is supported by the length and diameter frequency distribution of LWD (Fig 5.3). Free LWD had a higher frequency of smaller pieces than jammed wood in small streams; however, this pattern changed with increasing stream size (Fig 5.3 A-D). The diameter and length class distributions were different across stream size and jam class (Fig 5.3). Jammed wood had a higher frequency of low diameter and length classes than free wood. The shift was more predominant in transitional and medium streams, where the length class 0.5 and the diameter class 0.05 had greater relative frequencies of jammed wood (Fig 5.3 B/D).

The patterns in abundance and volume of jammed wood were different from those for free wood and the overall trend. The diameter and length class distributions were different across stream size and jam class. For these reasons, all additional analysis of position and orientation of wood was conducted within jam class only.

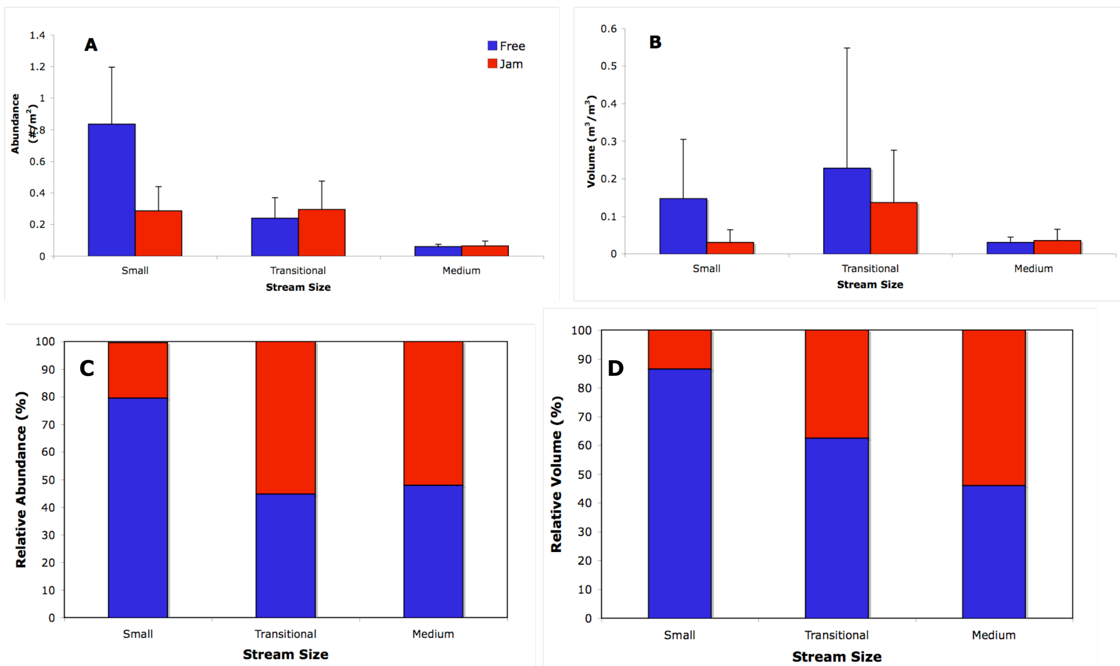


Fig 5.2 The patterns in the abundance (A/C) and volume (B/D) of wood jam class and stream size. Mean and standard deviation for each category (A/B), and relative values (C/D) were all analyzed to determine the spatial patterns across categories.

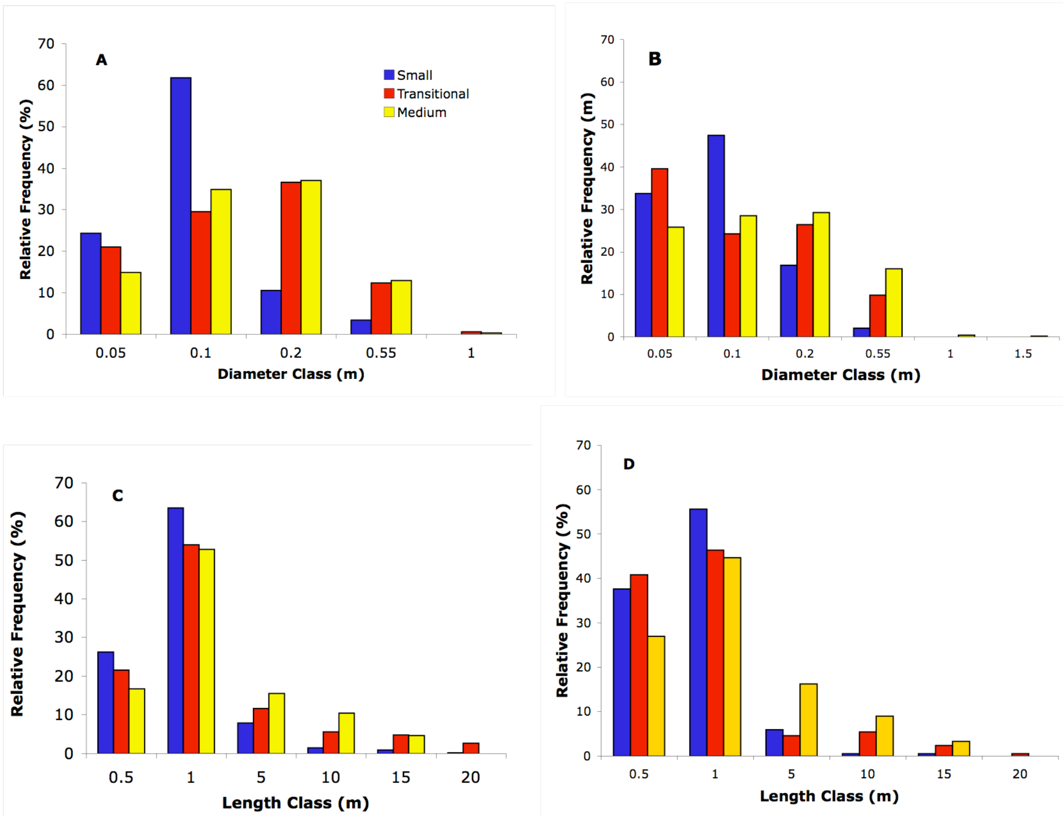


Fig 5.3 The frequency of LWD diameter (A/B) and length (C/D) class for free (A/C) and jammed (B/D) wood in the stream across three stream sizes.

5.3.3 Position

Patterns occurred in the position classes across stream size and jam categories. Wood abundance differed more than volume.

The scaled and relative abundance showed a clear pattern over stream size and position category that is similar to the overall results (Fig 5.4 A/C Table 5.5). The scaled abundance of LWD in all three position classes decreased with increasing stream size (Fig 5.4 A Table 5.5). For all three stream sizes and both jammed and free wood, bridged LWD had a lower mean abundance than LWD that was half in the bed and LWD that was fully in the bed was most abundant (Table 5.5). Only two position-by-stream size categories were significantly different across jam classes. The mean abundance of jammed LWD was less than free wood for (1) LWD that was half in the bed of small streams and (2) LWD that bridged transitional streams.

The frequency distribution of volume among position classes changed for both jammed and free wood with increasing stream size (Fig 5.4 B/D Table 5.5). The scaled volume of LWD increased from small to transitional streams and then decreased in medium streams for all position classes, except one. For free-bridged wood, mean volume was similar in small and medium streams (Fig 5.4 B). No position classes were significantly different within jam class across stream size (Table 5.5). Free wood had a significantly higher mean than the jammed wood in all position classes except fully-in-the-bed in transitional streams. For small and transitional streams, bridged and half-in-the-bed wood contributed more to the volume than fully-in-the-bed wood. Jammed and free wood had a different relative pattern in small streams (Fig 5.4 D, Table 5.5).

The size of pieces differed across position and jam class. Wood fully-in-the-bed had the highest abundance and lowest volumes for both jam classes. This suggests that the wood fully-in-the-bed was more numerous with smaller pieces relative to wood bridged, which had a higher volume but lower abundance for all stream sizes and jam classes. Wood half-in-the-bed also generally had a larger relative volume than abundance. For free wood in small and transitional streams, the bridged wood had the highest relative volume and lowest relative abundance, suggesting that free wood that was bridged in these stream sizes larger than jammed wood in the same position class.

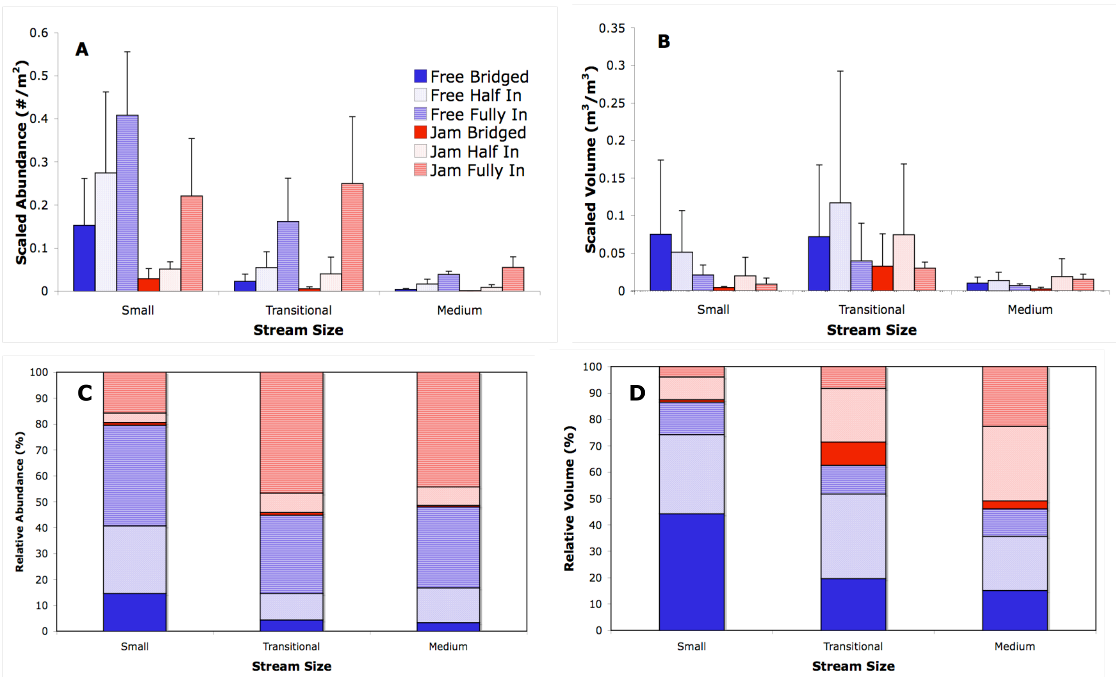


Fig 5.4 The patterns in the abundance (A/C) and volume (B/D) of wood by jam and position class. Mean and standard deviation for each category (A/B), and relative values (C/D) were all analyzed to determine the spatial patterns across categories.

Table 5.5 The positions across jam class and stream size for abundance and volume of wood. Numbers indicate significance across stream size within position and jam class. Letters indicate significance across position within size and jam class. * indicates significance within position and size class across jam class.

Size	**Free Wood**						**Jammed Wood**					
	Bridged		**Half In**		**Fully In**		**Bridged**		**Half In**		**Fully In**	
	Mean	**Group**	**Mean**	**Group**	**Mean**	**Group**	**Mean**	**Group**	**Mean**	**Group**	**Mean**	**Group**
Scaled Abundance (#/m^2)												
Small	0.153	1	0.274*	1	0.408	1	0.023	A1	0.051*	AB1	0.220	B1
Transitional	0.023*	A2	0.055	AB12	0.162	B12	0.005*	A12	0.040	A12	0.250	B12
Medium	0.004	A2	0.017	AB2	0.039	B2	0.001	A2	0.009	B	0.055	C2
Scaled Volume (m^3/m^3)												
Small	0.075*		0.051*		0.021*		0.004*		0.020*		0.009*	
Transitional	0.073*		0.117*		0.039		0.032*		0.074*		0.030	
Medium	0.010*		0.014*		0.007*		0.002*		0.019*		0.015*	

5.3.4 ORIENTATION

The patterns in the orientation classes were different across stream size, and jam categories (Fig 5.5, Table 5.6). The abundance in stream was more variable across orientation and stream size classes and the volume was more variable across jam classes.

For the scaled abundance values, wood classified as free generally decreased with increasing stream size and wood classified as jammed maintained similar values for small and transitional streams and then decreased (Fig 5.5 A). Perpendicular and diagonal wood was significantly more abundant in small streams than medium streams for both jam classes. In small streams, jammed parallel wood (0.023 pieces/m^2) had a significantly smaller mean than perpendicular wood (0.142 pieces/m^2). In small streams, parallel free wood (0.18 pieces/m^2) had a significantly higher mean than jammed parallel wood (0.023 pieces/m^2).

The relative abundance of free wood and jammed wood had different patterns with increasing stream size (Fig 5.5 C). For free wood, wood that was parallel to the stream was more abundant while the relative abundance of wood that was diagonal to the stream decreased with increasing stream size. For jammed wood, the relative abundance of wood perpendicular to the stream decreased with stream size, while wood parallel to the stream increased slightly. For both free and jammed wood, the relative abundance of parallel wood was less than that of diagonal or perpendicular wood.

Free wood contributed the most to the volume of LWD measured in small and transitional streams (Fig 5.5 B). Generally, transitional streams had the highest values for the volume measurements in all orientations. Free parallel and perpendicular wood in small and transitional streams had significantly greater volumes than jammed wood within the same stream-size and orientation categories. For both jammed and free wood in transitional streams, the volume of parallel wood was significantly lower than the volume of either diagonal or perpendicular wood. For free wood in small streams, perpendicular wood had a significantly greater volumes than either parallel or diagonal wood. For transitional streams, both diagonal and perpendicular wood were important to the volume distribution in streams. All three orientations had similar volumes in medium streams.

Visual patterns in the relative volume were across stream size, jam and orientation class: (1) the relative volume of perpendicular wood decreased with increasing stream size for free wood, while it increased in jammed wood; (2) the relative volume of parallel wood increased with stream size in both jam classes; and (3) the relative volume of perpendicular and diagonal wood always had a higher relative value than parallel wood (Fig 5.5 D).

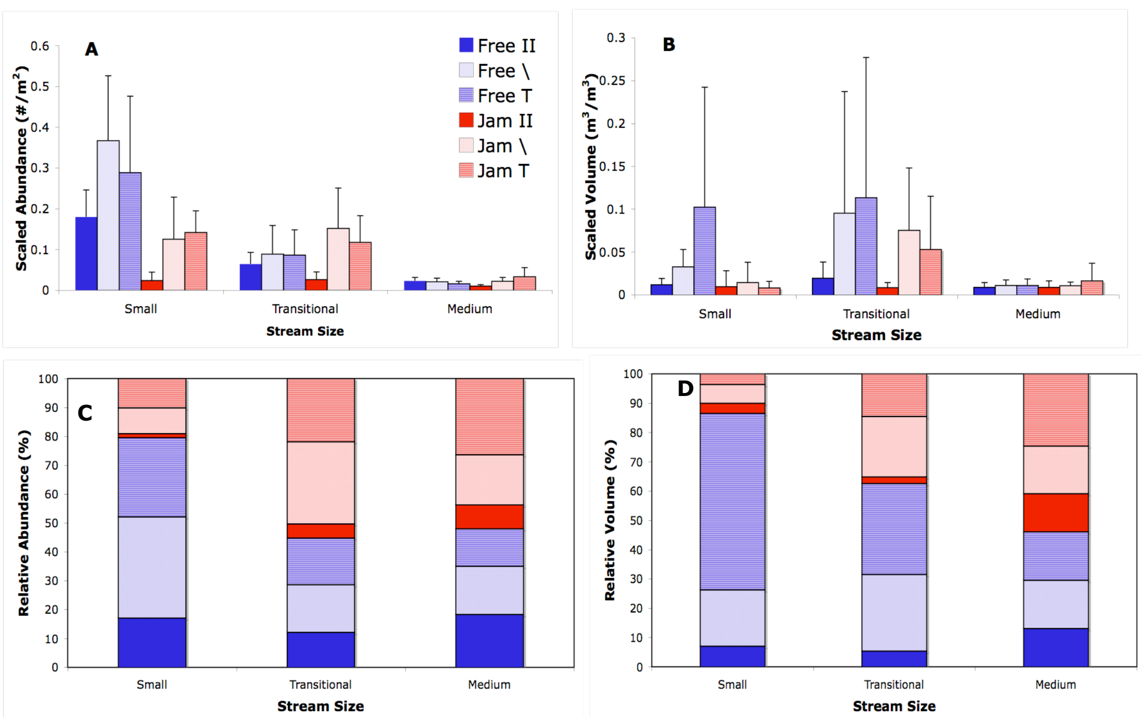


Fig 5.5 The abundance (A/C) and volume (B/D) of LWD by jam and orientation class. Mean and standard deviation for each category (A/B), and relative values (B/D) were analyzed to determine the spatial patterns across categories.

Table 5.6 The orientations across jam class and stream size for abundance and volume of wood. Numbers represent significance across stream size within position and jam. Letters represent significance across position within size and jam class. * Represents significant across jam category within position and size class.

Stream Size	Free Wood						Jammed Wood					
	Parallel		Diagonal		Perpendicular		Parallel		Diagonal		Perpendicular	
	Mean	Group	Mean	Group	Mean	Group	Mean	Group	Mean	Group	Mean	Group
Scaled Abundance (#/m^2)												
Small	0.180*	1	0.367	1	0.288	1	0.023*	A	0.125	AB1	0.142	B1
Transitional	0.065	12	0.089	12	0.086	12	0.026		0.152	1	0.117	12
Medium	0.023	2	0.021	2	0.016	2	0.010		0.022	2	0.033	2
Scaled Volume (m^3/m^3)												
Small	0.012*	A	0.033	A12	0.102*	B1	0.009*	B	0.014	1	0.008*	1
Transitional	0.020*	A	0.095	B1	0.113*	B1	0.008*	A	0.075	B2	0.053*	B2
Medium	0.009		0.011	2	0.011	2	0.009		0.012	1	0.016	12

5.3.5 LWD Jam Characteristics

The length of LWD jams increased with stream size (Fig 5.6 A/C) while the frequency of jams decreased (Fig 5.6 B/D). Jam length increased with stream size with medium streams having the most variable lengths (Fig 5.6 A/C). The jam length in medium stream sizes ranged from 0.9 m-51 m, while the range in small streams was the least with 0.1-4.5 m (Fig 5.6 A). The mean jam length increased significantly with stream size; for example,the mean jam length for medium streams was triple the mean for small streams (Fig 5.6 C). The median jam length for medium streams was 6.4 m, transitional 3.6 m and small 1.6 m. This suggests that even though medium streams had significant outliers (36 m and 51 m) (1) the mean was not significantly affected and (2) the pattern across stream size is valid.

Jam frequency (per 100 m^2) decreased in variability and value with increasing stream size (Fig 5.6 B/D). Small and transitional streams had a significantly higher mean jam frequency than medium streams (Fig 5.6 D). The small and transitional streams had a larger range in jam frequency over a smaller stream length than medium streams (Fig 5.6 B). This suggests that at small stream sizes the frequency of LWD jams is more variable, which may relate to transport capacity in streams. When the transport capacity is low, LWD will remain in the channel with little to no re-organization or transport.

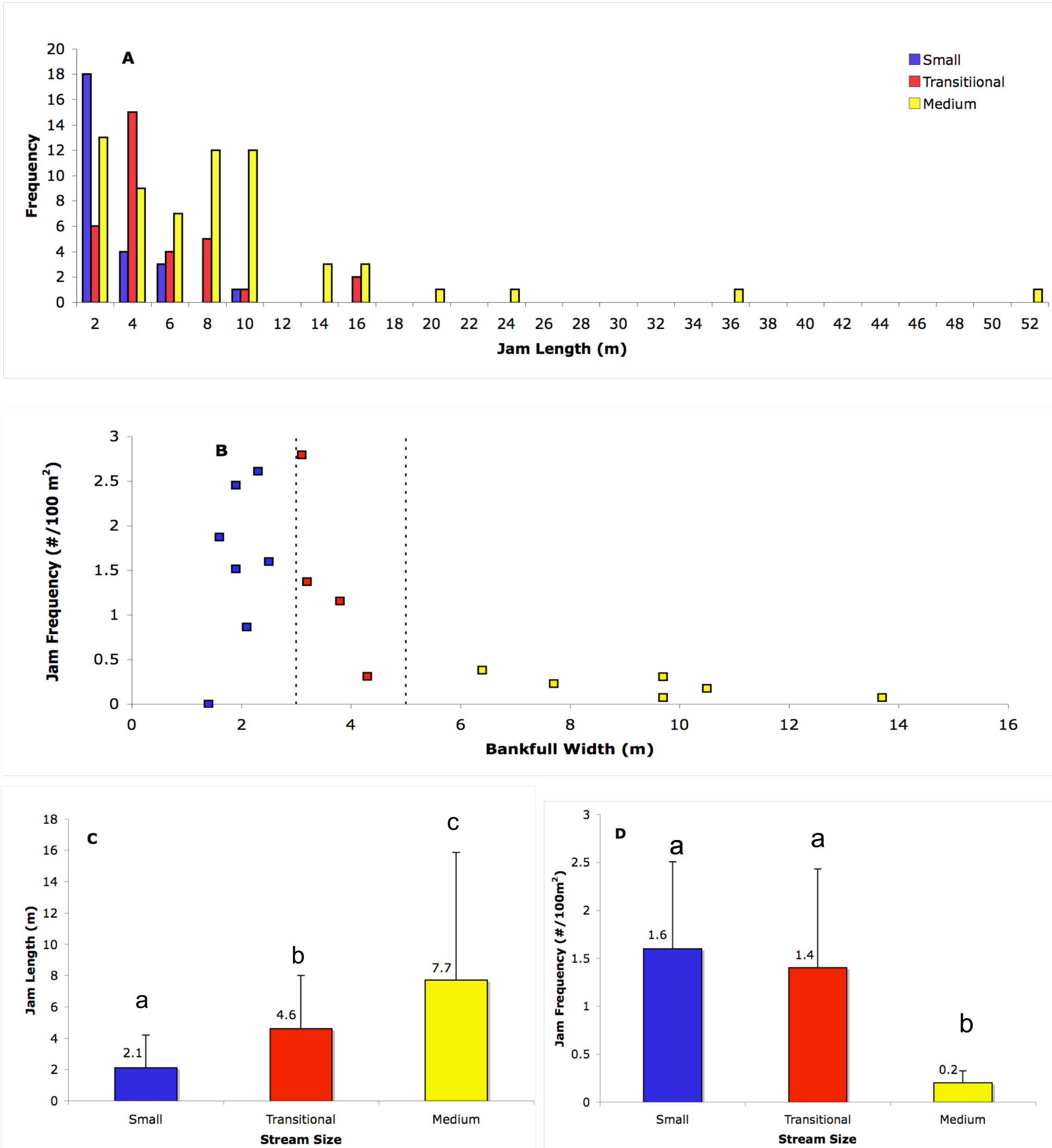


Fig 5.6 LWD jam characteristics. Fig A is a histogram that classified the length of LWD jams measured at each site into 2-meter length bins according to stream size. Fig B plots the frequency of jams relative to the scaled area of 100m^2 against bankfull width flow. The dashed lines represent the divisions of stream size used to calculate the mean. Fig C plots the mean (bar) and standard deviation (line) of jam length across stream size. Fig D plots the mean (bar) and standard deviation (line) of jam frequency across stream size. The letters above the bars in figure C/D represent the groupings of significantly different means.

5.4 DISCUSSION

The discussion is structured to explore the similarities and differences in the abundance and volume of wood across stream size and jam, position and orientation classes. Results of this research will be compared to current literature at multiple field sites worldwide. This was done to provide (1) a broad context to understand the results and (2) to understand the obtained patterns for streams in this study.

5.4.1 ABUNDANCE AND VOLUME ACROSS STREAM SIZE

Small streams had higher abundance of LWD than transitional or medium streams. This pattern has been observed in research at in multiple forest types: (1) boreal forests (Mossop and Bradford 2004); (2) sup-alpine forests (Richmond and Fausch 1995; Chen *et al*. 2006); (3) sub-boreal forests (Jones and Daniels 2008; Hinton, Alberta, Chapter 3 data), and (4) coastal forests (Gomi *et al.* 2001; Ralph *et al.* 1994). Review papers have also presented meta-analysis showing this pattern over multiple stream sizes and forest types (e.g. Gurnell 2003; Hassan *et al.* 2005). Fig 4.4 (Chapter 4) displayed wood abundance scaled by bankfull width for published data used a similar definition for the parameters of LWD and forest treatment (Old Growth). The results showed no difference amongst forest types and all showed a decreasing pattern with stream size. Robison and Beschta (1990) reported an increase in LWD abundance with increasing stream size; however, these results were scaled by length (100 m). When the data were scaled by area, the abundance decreased with stream size. This has two implications (1) scaling should be standardized across the field and (2) the same data interpreted in different can provide different patterns.

The volume of wood generally increased in streams up to 3 m wide and then decreased with increasing stream size. This pattern has been observed in multiple forest types: (1) sub-alpine forests (Chen *et al.* 2006) and (2) coastal forests (Robinson and Beschta 1990). The data from Hinton, Alberta from sites located in the sub-boreal forest showed a decrease in volume across stream sizes. However, almost all (16 of 21) of the Hinton sites were classified as small streams, only five were classified as transitional streams, and no streams were classified as medium. Given this uneven distribution of stream sizes, volume trends across stream sizes would be better represented if additional field sites were added at larger stream sizes to see if the pattern observed reflects (1) a measurement bias or (2) the true pattern. Fig 4.4 B (Chapter 4) displayed volume measures for multiple forest types and found that only the boreal forest sites were substantially lower than all other forest types. This implies that volume is a more sensitive measure than abundance across forest type.

The diameter and length of LWD increased with stream size, generally in the free wood more than the jammed wood. This finding suggests that the average size of LWD increased with stream size. This pattern has been reported across multiple forest types: (1) boreal forests (e.g. Mossop and Bradford 2004); (2) sup-alpine forests (e.g. Richmond and Fausch 1995; Chen *et al.* 2006); (3) sub-boreal forests (Jones and Daniels 2008), (4) coastal forests (e.g. Gomi *et al.* 2001; Ralph *et al.* 1994; Martin and Benda 2001) and (5) mixed broadleaf forests (Comiti *et al.* 2006). Even though the patterns were the same, the values for diameter and length were different across forest types. Webb *et al.* (2003), for example, reported a similar pattern in LWD diameter and length distribution in medium streams, however; the actual size of pieces was much smaller with >90% of the diameter being less than 30 cm and a large portion of the lengths being <2.5 m in length. Ralph *et al.* (1995) and Gomi *et al.* (2001) both reported wood diameters for small streams larger than for the field sites for this study (20-50 cm). Both of these studies were located in coastal forests in Western Washington and South Eastern Alaska respectively. This suggests that even though the patterns in piece size are constant across stream size, the forest structure will influence the absolute size of LWD.

The changes in size, volume and abundance of LWD suggest that as stream size increases, LWD is transported and re-organized within the channel. Smaller pieces are removed from the system or racked against LWD jams, which had a higher relative frequency of smaller LWD pieces at all stream sizes. The most mobile LWD has been reported to be less than bankfull width and the frequency of movement increases with stream size (Nakamura and Swanson 1994; Bilby and Ward 1985). As stream size increased, a larger portion of the pieces of LWD were less than bankfull width, therefore more re-organization occurred in larger stream sizes.

5.4.2 JAM CHARACTERISTICS

The abundance and volume of wood associated with LWD jams increased with stream size. In small streams, jammed wood was much less common than free wood, with the relative volume of free wood being 85%. In transitional and medium streams, the relative abundance and volume of jammed and free wood was closer to 50%. This is consistent with Gurnell (2002) finding who reported that the number of pieces of wood associated with LWD jams increases with stream size.

The frequency of logjams decreased decreased while jam size and length increased with increasing stream size. The pattern of decreasing jam frequency has been reported in a variety of forest types: (1) boreal forests (e.g Kreutzweiser *et al.* 2005); (2) coastal forests (e.g. Bilby and Ward 1989, Abbe and Montgomery 2002) and (3) mixed broadleaf forests (Comiti *et al.* 2006). The pattern of increasing jam size and/or length has also been reported in a variety of forest types: (1) boreal forests (e.g. Kreutzweiser *et al.* 2005), (2) coastal forests (e.g. Bilbly and Ward 1989, Martin and Benda 2001), (3) mixed broadleaf forests (Comiti *et al.* 2006) and (4) sub-alpine forests (Chen *et al.* 2006).

Jammed wood had a higher frequency of smaller diameter and length classes than free wood. This shift increased with stream size and changed the distribution of classes over stream size: transitional and medium streams had a higher frequency of the 0.5 m length than small streams. Gurnell (2002) reported that the size of LWD in jams decreases with stream size, while Abbe and Montgomery (2003) stated that jams generally consist of a few large key members that produce stability on which smaller pieces can become ‘racked’ or attached to by jamming. Smaller pieces that would normally not be able to withstand stream flows without being transported may be stabilized in a jam. This may explain why the jams in the medium and transitional streams have a shift in the size of LWD. Additionally, Martin and Benda (2001) reported that the length of pieces transported and the distance transported both increase with stream size. These pieces are transported until they become racked or jammed against the bank or as part of a LWD jam (Martin and Benda 2001).

5.4.3 Position and Orientation classes

For position the abundance of fully-in-the-bed was greater than half-in-the-bed which was greater than bridged and the volume of bridged was greater than half-in-the-bed which was greater than fully-in-the-bed for small streams and half-in-the-bed was greater than bridged or fully-in-the-bed for transitional and medium streams. In general, the abundance and volume of bridged wood decreased with stream size while the abundance and volume of fully-in-the-bed wood increased. The relative abundance and volume of wood half-in-the-bed changed little with stream size. Braudrick and Grant (2000) reported that LWD outside the flow was more stable. Chen *et al.* (2008) reported perpendicular abundance wood generally decreased while fully-in-the-bed wood increased across similar stream size categories that were used for this study. Jones and Daniels (2008) reported bridged wood to have the highest volume of all other position classes, with loose (in-the-bed) wood having the lowest volume, which is similar to the findings of this study. Comiti *et al.* (2006) reported a decrease in the volume of bridged wood with increasing stream size and most of the wood abundance was in the fully-in-the-bed category. The findings of this study are consistent with published results, though wood abundance was more often reported, making it difficult to compare wood volumes.

Patterns in the wood orientation were consistent with measures reported in other studies. In general, the abundance of diagonal and perpendicular wood exceeded parallel wood in small and transitional streams and diagonal wood exceeded perpendicular wood, which exceeded parallel wood in medium streams. For volume the general pattern for small streams was that perpendicular wood exceeded diagonal wood and both exceeded parallel wood. For volume in transitional streams, perpendicular and diagonal wood greatly exceeded parallel wood and in medium streams perpendicular wood exceeded both parallel and diagonal wood. Gurnell *et al.* (2002) reported a similar pattern: first order streams had more wood in the diagonal and perpendicular orientations than wood that was parallel to the stream. In fourth order streams, wood orientation was more evenly spread across the parallel, diagonal and perpendicular classes. Chen *et al.* (2006) reported perpendicular wood as having a high abundance across multiple stream sizes; however, parallel wood was found to have the second highest value across stream size with the diagonal class having the having the lowest relative values in large and small streams. Comiti *et al.* (2006) reported low numbers of perpendicular wood that decreased with stream size while parallel wood increased.

Position and orientation classes are important, as they have been related to transportation of wood in streams. Baudrick and Grant (2000) and Hygelund and Mange (2003) reported that wood parallel to the stream was more stable than either diagonal or perpendicular wood. The abundance of wood in the parallel orientation class increased with stream size while the abundance of perpendicular and diagonal wood decreased. This may indicate that pieces are moving from unstable orientations to more stable ones in larger stream sizes where flows can move the LWD. Fig 5.7 (A/B) shows the relative frequency of length class distributions within the perpendicular (A) and parallel (B) orientation. The length distribution of the perpendicular wood appears similar across all stream sizes with medium streams having a slightly higher relative frequency in larger pieces. The difference is in the fact that in small streams, for the 0.5 and 1 m class approximately 50% of the pieces were in the bed, with the larger class sizes being almost entirely bridged or half in the stream. For transitional and medium streams, the 0.5, 1 and 5 m size classes had > 50% of the pieces in the bed, suggesting that a larger portion of larger pieces of wood were perpendicular and in the stream bed for these streams. For all streams, the length of 1 m had the highest relative frequency of parallel wood. Fig 5.8 (A/B) shows the relative frequency of length class distribution of bridged (A) and fully in (B) position. There is a strong shift in the distribution of LWD length class sizes with stream size: medium and transitional steams have a much higher proportion of longer pieces bridged than small streams. Small streams have almost no pieces fully in the bed that were > 1 m in length, whereas transitional and medium have > 10% of the abundance of wood that was > 1 m length. The abundance and volume of wood bridged over the stream decreased with stream size, even though the average size of bridged wood increased. This may be related to the ratio of riparian tree height to bankfull width: smaller pieces of wood would be bridged over a stream with a smaller bankfull flow width. Baudrick and Grant (2000) reported that wood not interacting with flow was more stable than wood in the stream. Since more wood is either (1) half-in-the-bed or (2) fully-in-the-bed for the transitional and medium streams, more of the wood would be within the flow and therefore less stable than bridged pieces. If these pieces are less stable, then wood in these stream size positions would be more likely to be transported downstream.

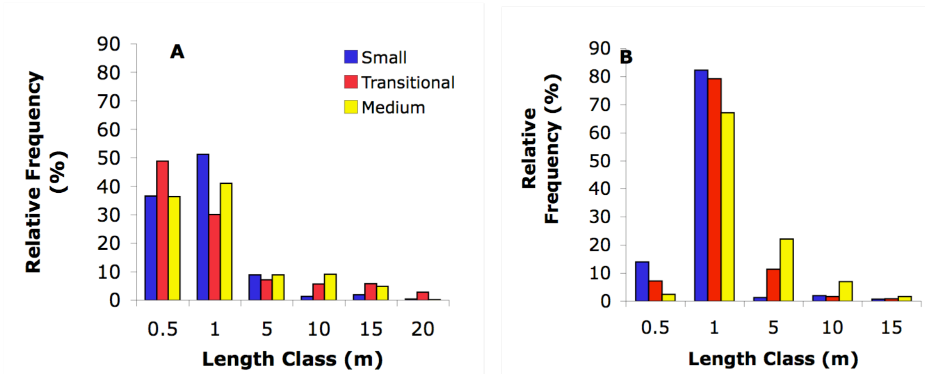


Fig 5.7 The length class distribution within perpendicular (A) and parallel (B) orientation classes across stream size

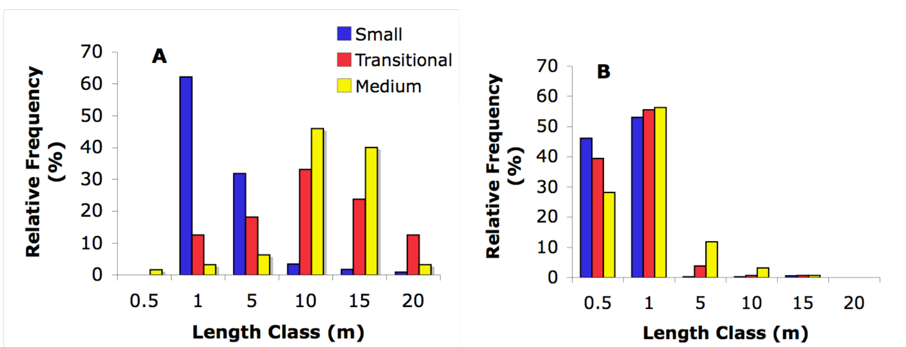


Fig 5.8 The length class distribution within bridged (A) and fully in (B) position classes across stream size.

5.5 Conclusions and Research Implications

This chapter had focused on the complex patterns in LWD and how these change with stream size, jam, orientation, and position classes. The abundance of LWD measured decreased with increasing stream size. Volume increased to transitional streams and then began to decrease. The size of LWD pieces increased with stream size. Jam characteristics and classes had different relationships: (1) jammed wood accounted for < 15% of the total abundance and volume in small streams and about 50% of the volume and abundance in transitional and medium streams; (2) the frequency of jammed wood per unit area decreased with increasing stream size; (3) the average length of individual log jams increased with stream size; and (4) the distribution of LWD diameter and length classes was skewed toward the smaller classes, this pattern was more pronounced in jammed wood than free wood and the difference in distribution between jammed and free wood increased with stream size. Position and orientation patterns in the stream were different across stream size and jam class. For position classes: (1) bridged wood both abundance and volume decreased with stream size; (2) jammed wood fully-in-the-bed wood increased for both volume and abundance with stream size; (3) For abundance fully-in-the-bed exceeded half-in-the-bed which exceeded bridged for all three stream sizes; and (4) for volume bridged exceeded half-in-the-bed exceeded fully-in-the-bed for small streams and half-in-the bed exceeded bridged which exceeded fully-in-the-bed for transitional and medium streams. For orientation classes: (1) diagonal and perpendicular wood exceeded the abundance and volume of parallel wood for small and transitional streams; and (2) for medium streams all three orientations fairly equally represented. All of these patterns have been documented in the literature at various field sites; however, none of the field sites were in the Northern Interior of BC. Additionally few of the papers reviewed reported the different patterns between jammed and free wood. This is significant as the scaled and relative values, as well as the diameter and length distribution were different across both stream size and jam class.

Patterns in LWD are complex and change with stream size. In order to present the most complete information about LWD patterns (1) abundance and volume measurements, (2) position and orientation classes and (3) jam classes should all be analyzed and presented. The length class distribution was different across position and orientation categories. This is related to bankfull width and the ability of stream to transport and reorganize LWD. This has implications for river restoration, as the appropriate number of logs within a range of size classes should be added in order to correctly ‘mimic’ natural input. Also, if jams are to be mimicked, then there is a larger variety of size classes needed in order to produce a jam using large key pieces and smaller racked and loose pieces.

6 CONCLUSIONS

This study assessed 18 streams in the Interior of British Columbia. The focus of this study was the spatial patterns of LWD for a range of stream sizes (bankfull width of 1.4-13.7 m) and forest types (SBS and SBPS BEC zones). In order to study the patterns in LWD, a definition and scaling technique were identified as the least biased in comparing figures over a variety of stream sizes. The remainder of this chapter will identify the main conclusions from the three data chapters and link these findings to possible future research.

There is no standard definition of the parameters used to define LWD or the scaling technique used to analyze and present data. As a result, it is difficult to make comparisons across field studies. This study has reported that: (1) the distribution of volume and abundance are affected by definition and scaling type; (2) small streams are more sensitive to changes in definition and scaling type; (3) abundance is a more sensitive measure than volume; (4) diameter is more sensitive than length; and, (5) patterns in the published literature change depending on scaling technique applied. These findings were discouraging as they suggested that meta-analysis would be difficult depending on multiple factors that can affect distribution. This research suggests that for definitions in field studies or meta-analyses: (1) the same definition should be used if possible; (2) the same diameter measurement should be used; (3) small streams should use a more inclusive definition; and (4) volume measurements should be compared as they are more resistant to definition. This research compared scaling by stream reach length, area and volume. Length was the most common measure to scale by and was found to be the most effected by changed in definition. LWD abundance and volume values should be scaled by stream volume if possible as this measure accounts for the most stream variables; however, due to limited measures at previous field sites, scaling by area may be used as a viable alternative that is also minimally affected by definition.

Riparian forest and stream characteristics influence the distribution of LWD within a stream. For the 18 field sites: (1) the distribution of diameter classes for LWD was affected by stream size more than forest type; (2) the riparian forests were structurally similar but had a different composition of riparian species; (3) the streams were physically different across stream size; and, (4) LWD abundance and volume identified physical stream characteristics for predictive models. These results suggested that the LWD distribution was more effected by stream size than forest type and, as such, the patterns could be compared across forest type in this study. When compared to abundance and volume measures from a variety of forest types reported in the literature, some patterns were similar but they also varied among forest types. Data from the boreal forest indicated that LWD volume was substantially lower than all other forest types. This comparison suggested that even thought the 18 field sites were more affected by stream size than forest type, forest type does become an influencing factor when there are larger structural differences between forest types.

Patterns in LWD were reported over stream size, jam, position and orientation class. This research found that (1) LWD abundance decreases with an increase in stream size, (2) volume decreases with an increase in stream size for streams with ≥3 m bankfull flow width, and (3) LWD jams have different patterns and size distributions than free wood. The findings within this chapter were generally consistent with published research; however, the are an important contribution to the literature because (1) a consistent definition and scaling technique were used; (2) multiple stream sizes were represented; and, (3) the northern Interior of BC has no published literature to my knowledge reporting on the patterns in LWD. LWD jams have been reported to have important geomorphic, biologic and hydrologic effects in streams in the PNW (e.g. Hogan 1987). This research has reported that LWD jams in the Interior of BC (1) increase in importance with stream size; (2) have a different size class distribution for both length and diameter than free wood; and, (3) have different patterns in the orientation and position of wood. For these reasons, the distinction of LWD into jammed and free wood was important for this research and is a practice that should be continued if additional research is done within the study area.

LWD as a field is extensively researched and cited for studies on geomorphology, hydrology, biology and habitat restoration (Gregory 2003). Scientists from multiple fields are measuring wood and reporting data about LWD for a variety of purposes. Because this field is so variable and extensive, it is vital that there be standardization across the field in measurement, analysis and presentation across the field in order for (1) valid comparisons across studies and (2) scientifically consistent work based on theory.

This thesis has provided a set of general rules for meta-analysis that will minimize the inconsistencies in the field by accounting for a variety of factors:

1. Use a single set of parameters to define LWD for analysis
    a. If not possible, try to use data from field sites that used the same diameter parameter
2. Scale the data by area or volume
    a. Volume accounts for more stream characteristics, but may be more difficult to apply retro-actively as it requires bankfull flow depth
3. Present the data for LWD abundance and volume
    a. Volume was less sensitive to definition than abundance
    b. Presenting both gives complete information of the LWD within a stream
4. Be aware of forest type.
    a. If the forests are structurally different, then results should be stratified by this characteristics.
    b. If the forest types are not structurally different, then comparisons across stream size only may be appropriate.
5. Be consistent in the presentation of patterns
    a. Explicitly state position and orientation categories
    b. Divide data into patterns within jam classes where appropriate
    c. Present both LWD abundance and volume data in order to provide complete information

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APPENDICES

APPENDIX A: LIST OF PAPERS FOR LITERATURE REVIEW

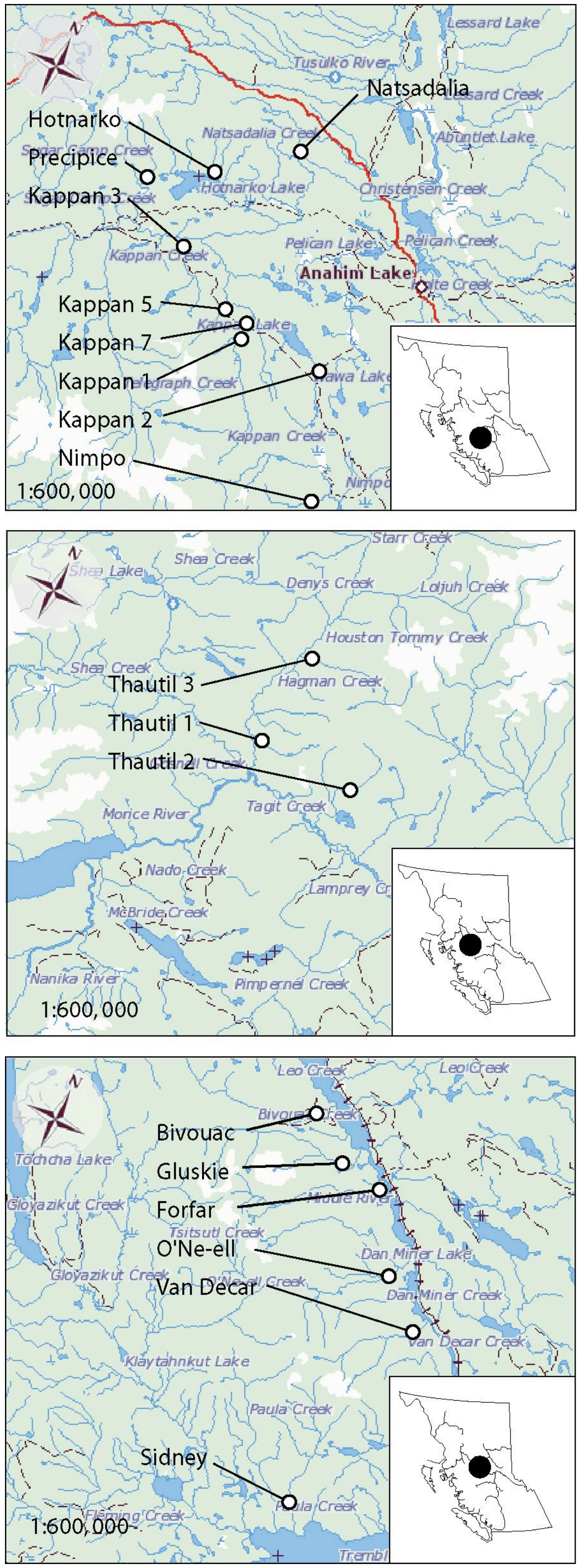
Key for Abbreviations in Table
L-length of wood in meters D-diameter of wood in centimeters O-was orientation recorded? P-was position recorded? DBF-was the bankfull flow depth recorded? WBF-was the bankfull flow width recorded? PNW-Pacific Northwest y-yes n-no

Authors	**Year**	**Scaling**	**L**	**D**	**O**	**P**	**DBF**	**WBF**	**Slope**	**Disturbance**	**General Location**
Abbe and Montogmery	1996	none	n	n	yes	yes	y	y	y	logging	PNW
Abbe and Montgomery	2003	length	1	10	yes	yes	y	y	y	none	PNW
Andrus *et al.*	1988	length	1	10	yes	yes		y	y	logging/ fire	PNW
Andreoli *et al.*	2007	area	1	10	yes	yes	y	y	y	none	Chili
Assani and Petit	1995	length	n	n	no	no	y	y	y	none	Europe
Ballie and Davies	2002	area/ length	n	10	yes	yes	n	y	y	plantation	New Zealand
Beechie *et al.*	2000	area	n	n	no	no	n	y	y	chronic/ episodic	PNW
Benda *et al.*	2003	length	1.8	8	yes	no	n	y	y	logging	PNW
Berg *et al.*	1998	length	1	8	yes	yes	y	y	y	logging	Nevada
Bilby and Likens	1980	area	n	n	no	no	y	y	y	logging	East Coast
Bilby and Ward	1991	length	2	10	no	no	n	y	n	logging	PNW
Bilby	1981	none	n	n	no	no	n	y	y	none	East Coast
Bilby	1984	none	n	15	yes	yes	n	y	y	logging	PNW
Borg *et al.*	2007	none	n	n	yes	no	y	y	y	none	Australia
Brummer *et al.*	2006	none	n	n	no	no	y	y	y	none	PNW
Buffington *et al.*	2002	none	n	n	yes	yes	y	y	y	none	PNW
Carlson *et al.*	1990	area	n	n	no	no	n	y	y	logging	PNW
Chen *et al.*	2006	area	1	10	yes	yes	y	y	y	none	Interior BC
Comiti *et al.*	2006	length	0.3	5	yes	yes	n	y	y	none	Europe
Cordova *et al.*	2007	area	1	10	no	yes	n	y	y	logging	Midwest
Curran and Wohl	2003	length	1	10	n/a	n/a	n	y	y	none	PNW
Diefenderfer and Montgomery	2009	none	n	n	no	no	n	y	y	none	PNW

Authors	Year	Scaling	L	D	O	P	DBF	WBF	Slope	Disturbance	General Location
Downs and Simon	2001	length/time	n	15	no	no	y	y	n	variable	Mississippi
Dudley and Fischenich	1998	none	n	n	no	no	y	n	n	none	PNW
Evens *et al.*	1993	length	n	2.5	no	no	n	y	y	plantation	New Zealand
Faush and Northcote	1992	length	1	10	yes	yes	y	y	y	logging	PNW
Faustini and Jones	2003	length	1	10	yes	yes	y	y	y	variable	PNW
Fetherston *et al.*	1995	none	1	10	yes	no	n	n	n	none	PNW
Fuchs *et al.*	2003	length	3	10	no	no	y	y	y	none	Interior BC
Gomi *et al.*	2001	length	0.5	10	yes	yes	n	y	y	logging/ landslides	PNW
Gurnell and Sweet	1998	length			no	no	n	y	y	none	UK
Gurnell and Gregory	1995	length	n	n	no	no	n	y	y	none	UK
Gurnell *et al.*	2000	area	1	10	yes	yes	y	y	y	none	Europe
Hartman *et al.*	1996	none	n	n	yes	yes	n	y	y	logging	PNW
Haschenburger and Rice	2004	none	na	na	no	n/a	n	n	n	logging	PNW
Hassan *et al.*	2007	none	n	n	yes	yes	y	y	y	Insect	Interior BC
Hedman *et al.*	1996	length	1.5	10	no	no	n	y	y	space/ time	East Coast
Heede	1985	none	n	n	no	yes	y	y	y	none	PNW
Hogan *et al.*	1998	width	n	yes	yes	yes	y	y	y	logging	PNW
Hogan	1987	none	n	10	yes	yes	n	y	y	logging	PNW
Inoue and Nakano	1998	length	1	10	no	yes	y	y	y	logging	Japan
Jackson and Sturm	2002	length	0.5	10	yes	yes	n	y	y	wind/log	PNW
Jones and Daniels	2008	area/length	1	8	no	yes	n	y	y	fire	Alberta
Kail	2003	none	n	n	yes	no	n	y	n	none	Europe
Keller and Tally	1979	area	n	10	yes	no	y	y	y	none	PNW
Koehn *et al.*	2004	area	n	n	yes	yes	n	y	y	none	Australia
Kraft and Warren	2003	none	1	10	yes	yes	n	y	y	ice storm	East Coast
Kreutzweiser *et al.*	2005	length	1	10	no	yes	n	y	y	logging	Boreal Shield
Benda *et al.*	2005	length	n	n	no	no	n	y	y	logging	PNW
Lienkaemper and Swanson	1987	area	1.5	10	yes	yes	n	y	y	none	PNW
Macdonald and Keller	1987	none	n	n	no	no	n	y	y	none	PNW
Marcus *et al.*	2002	length	1	10	yes	no	y	y	y	fire	Midwest
Martin and Benda	2001	length	1.5	10	no	no	n	y	y	windthrow	PNW
May and Gresswell	2003	length/time	2	20	no	no	n	y	y	fire	PNW
McHenry *et al.*	1998	none	3	10	yes	yes	n	y	y	logging	PNW
McIlroy *et al.*	2008	length	3	10	no	yes	n	y	y	none	Midwest
Montgomery *et al.*	1995	none	n	n	no	no	n	y	y	logging	PNW

Authors	Year	Scaling	L	D	O	P	DBF	WBF	Slope	Disturbance	General Location
Montgomery *et al.*	2003	none	yes		no	no	y	y	y	logging	PNW
Mossop and Bradford	2004	area/length	1	10	no	no	n	y	y	none	Yukon
Moulin and Piegay	2004	none	n	range	no	no	n	n	n	none	Europe
Murphy and Koski	1989	none	3	10	no	no	y	y	y	none	PNW
Nakamura and Swanson	1993	area	n	n	no	yes	n	y	y	none	PNW
Pettit *et al.*	2006	length	n	y	yes	yes	n	y	y	none	South Africa
Piegay *et al.*	1998	area	4	range	yes	yes	y	y	y	farmland	Europe
Ralph *et al.*	1994	length	3	10	no	yes	n	n	y	logging	PNW
Richmond and Fausch	2002	length	1	10	yes	yes	y	y	y	logging	Midwest
Richmond and Fausch	1995	area/length	3	10	yes	yes	y	y	y	none	Midwest
Robinson and Bescheta	1990	area/length	1.5	20	yes	yes	y	y	y	none	PNW
Wallerstein and Thorne	2004	length	1	10	no	no	y	y	y	none	Mississippi
Ward and Aumen	1986	length	n	10	no	yes	y	y	y	none	PNW
Warren *et al.*	2008	area/length	1	10	yes	no	y	y	y	none	East Coast
Webb and Erskine	2003	area/ length	n	10	yes	no	y	y	y	none	Australia
Webster *et al.*	1999	none	n	n	n/a	n/a	n	n	y	none	North Carolina
Wyzga and Zawiwjska	2005	area	1	10	no	no	y	y	y	flood	Europe
Young	1994	length	2	15	yes	yes	n	y	y	fire	Midwest
Young *et al.*	1999	area	1	15	yes	no	n	y	y	logging/fire	PNW
Zelt and Wohl	2004	length	2	15	no	yes	y	y	y	fire	Midwest
Chen *et al.*	2008	area	1	10	yes	yes	y	y	y	none	Interior BC

APPENDIX B: MAP OF THE LOCATION OF THE STUDY SITES



Map from Hassan and Hogan (2007)

APPENDIX C: THE SITE-SPECIFIC STREAM AND RIPARIAN CHARACTERISTICS

Table C.1 Specific study site characteristics. The six morphometric regions have been identified so that comparisons can be made between the general and the specific sites.

Study Reach	Stream Characteristics				Riparian Characteristics	
	Bankfull Width (m)	Bankfull Depth (m)	Slope (m/m)	D_{95} (mm)	Stems/ha	Basal area/ha
Hotnarko						
Hotnarko	2.5	0.42	0.043	35	4100	356559
Kappan 4	2.3	0.52	0.075	47	11850	577958
Kappan 5	1.6	0.46	0.061	83	2850	487232
Precipice						
Precipice	3.1	0.60	0.024	89	4100	626159
Nimpo	1.4	0.58	0.026	72	2850	614457
Kappan 3	1.9	0.76	0.033	96	3450	541043
Kappan						
Kappan 1	1.9	0.34	0.014	9	700	28057
Natsidalia	2.1	0.61	0.028	91	3350	1152489
Kappan 2	1.7	0.55	0.028	82	6750	701763
Thautil						
Thautil 1	3.8	0.76	0.046	323	4100	2420347
Thautil 2	4.3	0.83	0.031	244	1600	843006
Thautil 3	3.2	0.41	0.046	133	3250	633039
O'Ne-el						
O'Ne-el	13.7	1.01	0.016	156	1850	68197
Bivouac	7.7	0.95	0.03	216	3950	239168
Sidney	6.4	0.83	0.021	96	3100	430004
Forfar						
Forfar	9.7	0.87	0.008	216	2700	46279
Gluskie	9.7	0.91	0.012	214	4000	250445
Van decar	10.5	0.81	0.012	147	2100	188409

APPENDIX D: RIPARIAN FOREST DISTRIBUTION

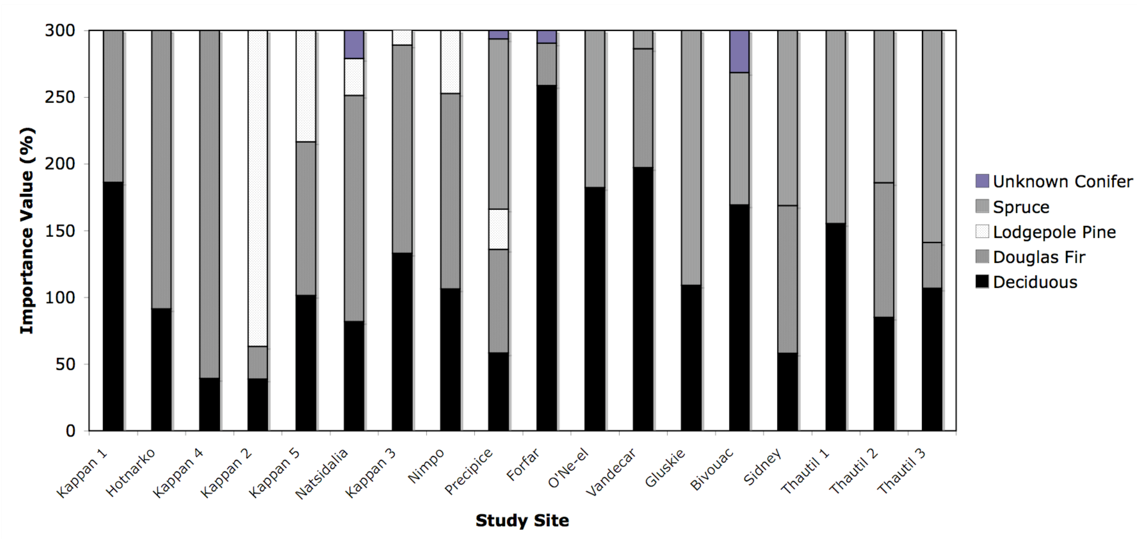


Fig D.1 The importance values for the species distribution of all 18 study sites. The nine columns on the left represent study sites in the pine forest and the nine columns on the right represent study sites in the pine-spruce.

APPENDIX E: RESULTS FROM REGRESSIONS FOR PREDICTING STEPWISE MODELS

Table E.1 Results from the regressions for predicting the abundance of scaled LWD found at each site.

Parameters	Significant Parameters (0.05)	Model P-value	Intercept P-value	Assumptions for Residuals		
				Linear	Equal Variance	Normal
Log₁₀ bankfull width (m) Slope (m/m) *Log₁₀* slope (m/m) Bankful width (m) Shannon H1 Log_{10} D_{95} (mm)	None	0.02	0.68	No	No	No
Log_{10} bankfull width (m) Slope (m/m) Log_{10} slope (m/m) Bankful width (m) Shannon H1	Log_{10} bankfull width (m)	0.01	0.72	No	No	No
Log_{10} bankfull width (m) Slope (m/m) Log_{10} slope (m/m) Bankful width (m)	Log_{10} bankfull width (m)	0.008	0.86	No	Yes	Yes
Log_{10} bankfull width (m) Slope (m/m) Log_{10} slope (m/m)	Log_{10} bankfull width (m)	0.006	0.45	No	Yes	Yes
Log_{10} bankfull width (m) Slope (m/m)	Log_{10} bankfull width (m)	0.004	0.03	No	Yes	Yes
Log_{10} bankfull width (m)	Log_{10} bankfull width (m)	0.0006	<0.0001	Yes	Yes	Yes

Table E.2. The results from the regressions for predicting the Log_{10} abundance of scaled LWD found at each site

Parameters	Significant Parameters (0.05)	Model P-value	Intercept P-value	Assumptions for Residuals		
				Linear	Equal Variance	Normal
Log_{10} bankfull width (m) Slope (mm) Log_{10} distance-glide (%) Importance value of Douglas-fir (%)	*None*	0.003	0.77	Yes	No	No
Log_{10} bankfull width (m) Slope (mm) Log_{10} distance-glide (%)	Log_{10} bankfull width (m)	0.0007	0.34	Yes	No	No
Log_{10} bankfull width (m) Slope (mm)	Log_{10} bankfull width (m)	0.0001	0.31	Yes	No	Yes
Log_{10} bankfull width (m)	Log_{10} bankfull width (m)	<0.0001	0.0039	Yes	Yes	Yes

Table E.3 The results from the regressions for predicting Log_{10} volume of scaled LWD found at each site

Parameters	Significant Parameters (0.05)	Model P-value	Intercept P-value	Assumptions for Residuals		
				Linear	Equal Variance	Normal
Bankfull depth (m) Distance-pool (%) Shannon H1 *Log₁₀* distance-glide *Log₁₀* Importance value Douglas-fir *Log₁₀* elevation-pool Basal area per hectare (m^2/ha) *Log₁₀* Basal area per hectare (m^2/ha)	Bankfull depth (m)	0.06	0.25	No	No	No
Bankfull depth (m) Distance-pool (%) Shannon H1 *Log₁₀* distance-glide *Log₁₀* Importance value Douglas-fir *Log₁₀* elevation-pool Basal area per hectare (m^2/ha)	Bankfull depth (m)	0.0002	0.2	No	No	No
Bankfull depth (m) Distance-pool (%) Shannon H1 *Log₁₀* distance-glide *Log₁₀* Importance value Douglas-fir *Log₁₀* elevation-pool	Bankfull depth (m) Distance-pool (%)	<0.0001	0.13	Yes	No	No
Bankfull depth (m) Distance-pool (%) Shannon H1 *Log₁₀* distance-glide *Log₁₀* Importance value Douglas-fir	Bankfull depth (m) Distance-pool (%) Shannon H1	<0.0001	0.07	Yes	No	No
Bankfull depth (m) Distance-pool (%) Shannon H1 *Log₁₀* distance-glide	Bankfull depth (m) Shannon H1 *Log₁₀* distance-glide	<0.0001	0.22	Yes	No	No
Bankfull depth (m) Distance-pool (%) Shannon H1	Bankfull depth (m) Distance-pool (%) Shannon H1	<0.0001	0.023	Yes	No	No
Bankfull depth (m) Distance-pool (%)	Bankfull depth (m) Distance-pool (%)	<0.0001	0.001	Yes	No	Yes
Bankfull depth (m)	Bankfull depth (m)	<0.0001	0.006	Yes	Yes	Yes

Table E.4 The results from the regressions for predicting volume of scaled LWD found at each site

Parameters	Significant Parameters (0.05)	Model P-value	Intercept P-value	Assumptions for Residuals		
				Linear	Equal Variance	Normal
Log_{10} bankfull depth (m) Bankfull depth (m) Log_{10} D95 (mm) D_{95} (mm) Slope (m/m) Log_{10} importance value of Douglas-fir Basal area per hectare	Bankfull depth (m)	0.06	0.30	No	No	No
Log_{10} bankfull depth (m) Bankfull depth (m) Log_{10} D95 (mm) D_{95} (mm) Slope (m/m) Log_{10} importance value of Douglas-fir	Log_{10} bankfull depth (m) Bankfull depth (m)	0.001	0.15	No	No	No
Log_{10} bankfull depth (m) Bankfull depth (m) Log_{10} D95 (mm) D_{95} (mm) Slope (m/m)	Log_{10} bankfull depth (m) Bankfull depth (m)	0.0009	0.07	No	No	No
Log_{10} bankfull depth (m) Bankfull depth (m) Log_{10} D95 (mm) D_{95} (mm)	Log_{10} bankfull depth (m) Bankfull depth (m)	0.0007	0.013	Yes	No	No
Log_{10} bankfull depth (m) Bankfull depth (m) Log_{10} D95 (mm)	Log_{10} bankfull depth (m) Bankfull depth (m)	<0.0001	0.0029	Yes	No	Yes
Log_{10} bankfull depth (m) Bankfull depth (m)	Log_{10} bankfull depth (m) Bankfull depth (m)	<0.0001	0.0015	Yes	Yes	Yes

APPENDIX F: EXAMPLE SUMMARY CHART

Site	Size[1]	Jams[2]	Amount/area[3]	Volume/volume[4]
1	Small	1	0.678137652	0.081086539
2	Small	1	0.494	0.044827678
3	Small	1	1.139130435	0.28730075
4	Small	1	0.520588235	0.035153918
5	Small	1	1.3375	0.070198205
6	Small	1	0.619047619	0.101894564
7	Small	1	0.589473684	0.072197865
8	Small	1	1.304761905	0.483828903
9	Transitional	1	0.16344086	0.061993412
10	Medium	1	0.063298969	0.043414415
11	Medium	1	0.038255211	0.010580648
12	Medium	1	0.055411255	0.021731302
13	Medium	1	0.051077788	0.025980277
14	Medium	1	0.068542569	0.033181835
15	Medium	1	0.081423611	0.048270981
16	Transitional	1	0.218228498	0.082289569
17	Transitional	1	0.429375	0.707595541
18	Transitional	1	0.146770026	0.06071751
1	Small	2	0.339068826	0.012201705
2	Small	2	0.206	0.011584154
3	Small	2	0.484782609	0.076619006
5	Small	2	0.1625	0.009649888
6	Small	2	0.101731602	0.002237206
7	Small	2	0.424561404	0.071226041
9	Transitional	2	0.491397849	0.15217672
10	Medium	2	0.046494845	0.028459509
11	Medium	2	0.03649635	0.009571527
12	Medium	2	0.047878788	0.027575274
13	Medium	2	0.056138707	0.027988743
14	Medium	2	0.086435786	0.025365134
15	Medium	2	0.114756944	0.095540588
16	Transitional	2	0.294608472	0.031239589
17	Transitional	2	0.3375	0.327656825
18	Transitional	2	0.056847545	0.035642414

1. Stream Size Class: three possible levels
2. Jam class: one is wood free in the stream and two is wood within a jam
3. Abundance/area: the absolute abundance of wood per unit area measured at each site within the stream size and jam class
4. Volume/volume: the absolute volume of wood per unit volume of stream measured at each site within stream size and jam class

APPENDIX G: INCLUDES FIELD SITES FROM > 20 M BANKFULL WIDTH.