THE EFFECTS OF WILDFIRE DISTURBANCE AND STREAMSIDE CLEARCUT HARVESTING ON INSTREAM WOOD AND SMALL STREAM GEOMORPHOLOGY IN SOUTH-CENTRAL BRITISH COLUMBIA

by

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ABSTRACT

Few field studies have assessed the temporal and spatial dynamics of wood in small streams (bankfull widths < 5 m) flowing through forest ecosystems dominated by stand replacing wildfires. Comparisons of instream wood loads associated with clearcut harvesting, wildfire, and undisturbed, old forests are also scarce. The two main objectives of this research were: (1) to document the temporal and spatial variability of wood and its geomorphic role in relation to stand development stage; and (2) to compare wood loads and its geomorphic role in relation to streamside clearcut harvesting, wildfires and older, undisturbed forest stands. This research focused on 38 small streams with gradients less than 14% situated in the plateau regions of south-central British Columbia, Canada.

A distinct temporal trend in wood loading was observed, with elevated volumes present 30-50 years subsequent to the wildfire disturbances following a "reverse J-shaped" trend in relation to time since the last major wildfire disturbance. The number of wood pieces was highly variable and few of the wood characteristics exhibited a significant trend in relation to time since the last major wildfire disturbance. Except at the smallest spatial scale (<3 m segments longitudinally along the stream) the spatial distribution of wood followed a random pattern with no trend, indicating that wood loads are related to local wood recruitment processes associated with episodic or chronic tree mortality and low wood transport.

Instream wood volumes were three times higher in streams recently (30 – 50 years ago) disturbed by wildfire as compared to the older riparian forest stands, confirming that

wildfire disturbance is an important mechanism to recruit wood into streams. No significant differences in wood loads were identified between the streamside clearcut streams and the wildfire-disturbed or older, undisturbed streams. The lack of reductions in wood loads are likely related to the low transport capacity of our study streams, retention of non-merchantable trees and recruitment of slash from harvesting. A lack of morphologic variability was observed in relation to the disturbances indicating that the streams included in this study are relatively robust and unresponsive to wildfire or streamside clearcut harvesting disturbances.

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CHAPTER 1

INTRODUCTION

1.1 STATEMENT OF ISSUES

Riparian management and harvesting adjacent to small streams have recently become a growing concern, especially since these streams are typically managed to a lower level of riparian protection than are larger streams (Moore and Richardson 2003; Danehy and Ice 2007). This concern stems from recognition of the important role that these streams and associated riparian areas play in maintaining various structural, functional and ecological processes at the local stream reach scale and downstream at the larger stream network scale. Recent research has highlighted the importance of these small streams in supporting various aquatic organisms, supply of invertebrates, wood, sediment and nutrients to downstream systems (e.g. Gomi et al. 2002; Wipfli et al. 2007; Richardson and Danehy 2007). Also, small streams cumulatively constitute the majority of all stream channels by both sheer number and length within a given forested watershed (Beschta and Platts, 1986; Gomi et al. 2002) with these streams flowing directly through large areas of economically important and productive areas for timber supply. Small streams typically constitute 60 to 80% of the total stream length in mountainous watersheds (Schumm 1956).

As result of this heightened level of concern, numerous riparian management laws, rules and guidelines have been revised or developed in western North America to better protect small streams and their associated riparian areas (Lee et al. 2004). Examples include the Forest Practices Code of BC (B.C. Ministry of Forests 1995a), Okanagan-Shuswap Land

Resource Management Plan (Okanagan-Shuswap LRMP 2000), Plum Creek Timber Company Native Fish Habitat Conservation Plan (Plum Creek Timber Company 1999) and the Forest Ecosystem Management Assessment Team approach (FEMAT 1993). Even with this level of effort, current policies on riparian management appear to be arbitrary, with limited field-based research to confirm whether current policies are actually avoiding harmful impacts to stream functions. This intuitive approach is especially apparent in interior, montane forest types of western Canada, where the majority of riparian and stream management strategies are based primarily on research that has been conducted in rain-dominated coastal regions of the Pacific Northwest (Moore and Richardson 2003). Limited research information currently exists for the drier interior, montane forest regions that have historically been dominated by major disturbances related to wildfires or mountain pine beetle epidemics. As a result of the lack of science-based information, conflicts and differing opinions continue to cloud forest and streamside management decisions (Adams 2007).

One of the major differences that separate coastal regions of the Pacific Northwest from montane forest regions in the interior of British Columbia is the role that major disturbances such as stand replacing wildfires have played in shaping forest ecosystems. For example, stand replacing forest fires have been reported to occur at mean return intervals of 125 to 150 years in interior, montane forests of British Columbia as compared to frequencies of 250 to 350 years in coastal regions (B.C. Ministry of Forests 1995b; Wong et al. 2003). These pre-management fires have created a patchwork of varying forest cover ages and species compositions throughout much of the interior of

British Columbia. In addition, much of the instream wood research has been conducted in "old growth" forest types utilizing short-term field measurements limited to one point in time, with limited information available regarding the long-term dynamics of instream wood associated forest types that would have experienced relatively frequent stand replacing fires. This lack of temporal information makes it difficult to know what led to an observed wood loading and how the wood loading will change in the future. The geomorphic role of wood may also change through time; therefore, an improved understanding into the long-term dynamics of instream wood and its geomorphic role through time can provide important insight into future channel conditions. Furthermore, much of the instream wood research in small streams has focused on steep headwater streams of the Pacific Northwest that are dominated by geomorphic processes such as earth flows, gully erosion or debris flows, with limited research in regions where small streams "… have been formed under different climatic conditions and therefore represent "relic" channels that undergo no modern-day mass wasting processes…" (May 2007). Much of the interior of western Canada is dominated by relatively low gradient stream channels where mass wasting disturbances are unlikely or infrequent; therefore, a noteable contribution of this thesis is focused on small streams that are not dominated by modern-day mass transport processes.

Information on instream wood dynamics also becomes particularly important in the current era of forest management strategies with forest managers trying to understand and emulate natural disturbance (Attiwill 1994; Rogers 1996). Natural disturbances have been recognized as a driver in maintaining ecological function, complexity and diversity in both forest and aquatic ecosystems (Resh et al. 1988; Attiwill 1994; Franklin et al. 2002; Bisson et al. 2003). Silviculture strategies that emulate natural disturbance have been promoted as part of a natural disturbance paradigm for forest management (Attiwill 1994; Rogers 1996; McRae et al. 2001; Franklin et al. 2002). This paradigm has led to a debate about whether clearcut harvesting mimics natural disturbance (Keenan and Kimmins 1993; McRae et al. 2001).

1.2 PURPOSE AND OBJECTIVES

The primary purposes of this research were two-fold. The first purpose was to document the temporal and spatial variability of instream wood and its geomorphic role associated with stand replacing wildfires and subsequent regeneration of riparian forest stands in small streams of the south-central interior of British Columbia. The second purpose examined the influence that streamside clearcut logging had on instream wood and geomorphology in small streams of south-central interior of British Columbia in comparison to streams that had been affected by recent (<50 years) stand replacing wildfires and to streams that flow through relatively undisturbed older riparian forest stands.

The specific objectives of the research were to:

1. quantify the temporal and spatial distribution of instream wood in small streams in relation to various riparian forest stand development stages and the time since the last major disturbance.

2. compare instream wood loads and the spatial distribution of instream wood in relation to streamside clearcut harvesting, stand replacing wildfires and older riparian forest stands.

3. evaluate the temporal variation of various instream wood characteristics (i.e. size, decay state, orientation, position, input source and function) in relation to riparian forest stand development stages and compare these characteristics in relation to the riparian stand conditions described in #2 above.

4. evaluate various channel morphology characteristics and the geomorphic role of wood in relation to riparian forest stand development stages and compare these channel morphology characteristics in relation to the riparian stand conditions described in #2 above.

Specific hypotheses associated with these objectives are included in each of the following research chapters.

To address these objectives, instream wood and channel morphology data were collected from 38 study streams situated in the Okanagan Highlands and Thompson Plateau of the south-central interior of British Columbia. The data from these study streams were further grouped into two main sets. The first grouping of data (i.e. stand development stages) included 26 of the 38 study streams. These streams flowed through riparian forest stands of various ages (32 to 200 years old) that had not been influenced by streamside clearcut harvesting. The second grouping of data (i.e. disturbance categories) also included 26 of the 38 study streams and included only those streams that had been influenced by streamside clearcut harvesting in the last 40 years, stand replacing wildfires within the last 50 years or streams that flowed through riparian forest stands that were transitioning into an old growth state (> 120 years old).

For clarification the following definitions apply to this work:

- "Small Streams" are defined as low order stream channels that are less than 5 m in bankfull width with average annual streamflow approximately less than 0.06 m^3/s (~2 ft^3/s). This definition is based upon that proposed by Danehy and Ice (2007). The streams studied in this work also adhere to the geomorphic matrix of relative wood size and relative channel size proposed by Hassan et al. (2005a). Based on this matrix the study streams are considered small since wood size is large relative to channel size with ratios of wood length to bankfull width exceeding 1.0 and ratios of wood diameter to bankfull depth exceeding 0.3.
- "Wood" or "Instream Wood" is used throughout this work as opposed to commonly used terms such as large woody debris, coarse woody debris or large organic debris. As proposed by Gregory et al. (2003), this terminology was adopted to avoid the negative connotation of the term "debris" and to provide a simpler and more accurate term.

- "Wood load" is defined as the number or volume of wood inventoried in the study streams.
- "Disturbance" refers to "…any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment" (Pickett and White 1985).
- "Major Disturbances" or "stand-replacing disturbances" are disturbances that remove or kill all the existing trees above the forest floor vegetation (Oliver and Larson 1996, p. 95).
- "Minor Disturbances" are disturbances that leave some of the predisturbance trees alive (Oliver and Larson 1996, p. 95).

1.3 THESIS OUTLINE

The findings of this research are organized into eight chapters. Chapter 2 provides an overview of the current state of knowledge regarding the geomorphic role of wood and the dynamics of wood in small streams in relation to major disturbances such as stand replacing wildfires or streamside clearcut harvesting. This chapter provides the foundation for the following research chapters. Chapter 3 presents a description of the study area along with an assessment of the similarity between study stream basins. Chapters 4 to 7 present the research results. Each of the research chapters includes a review of literature, research objectives and hypotheses pertinent to that chapter, along with sections on methods, results, discussion and conclusions. Although each chapter uses distinct approaches, the chapters build upon each other to provide an integrated understanding of the influence that wildfire disturbances or streamside clearcut harvesting have on instream wood and channel morphology in small streams of South-Central British Columbia. Chapter 4 addresses the temporal dynamics of instream wood loads and associated characteristics in relation to various riparian stand development stages and the time since the last major disturbance. Chapter 5 compares instream wood loads associated with streamside clearcut harvesting, recent stand replacing wildfire disturbances and riparian forests that are transitioning to old growth. Chapter 6 investigates the influence of various stand development stages, wildfires and streamside clearcut harvesting have on channel morphology. The spatial distribution of wood is analyzed in Chapter 7 in relation to the riparian stand development stages, stand replacing wildfires and streamside clearcut harvesting. This chapter also includes an evaluation of study reach lengths and sample sizes used in this study to improve future studies or forest management/monitoring activities. The final chapter, Chapter 8, provides a summary of major findings and key contributions of research as well as recommendations for further research.

CHAPTER 2

INSTREAM WOOD, SMALL STREAMS AND DISTURBANCES

2.1 INTRODUCTION

Emulating natural disturbance as a forest management strategy is seen by many as critical to sustaining the biological, physical and biodiversity components of forest and aquatic ecosystems (Bisson et al. 2003; Nitschke 2005). Ecosystems dominated by major stand replacing wildfires appear to be the most suitable for such forest management strategies, prompting several comparisons between forest harvesting and wildfire disturbances. In terrestrial and aquatic environments, comparisons between wildfire and forest harvesting have focused on terrestrial wood loads, water quality and quantity, stream temperatures and sedimentation (e.g. Keenan and Kimmins 1993; Tinker and Knight 2000; Carignan et al. 2000; Lamontagne et al. 2000; Nitschke 2005), with only a few studies (e.g. Bragg 2000; Benda and Sias 2003) evaluating the dynamics of instream wood between wildfire and forest harvesting. None of these studies compared wood loads, characteristics and morphologic differences between streams affected by wildfires and forest harvesting.

This chapter summarizes the current state of knowledge regarding the effects of wildfire and forest harvesting disturbances on wood loads, and provides a foundation to the research included in this thesis. This chapter begins by reviewing the ecological and geomorphic role of wood in small streams. It then discusses the main input, transport and output processes that control the storage dynamics and fluxes of instream wood. This is followed by a discussion regarding the temporal and spatial dynamics of wood in the context of wildfire and forest harvesting disturbance. A comparison between the effects on channel morphology of forest harvesting and wildfire disturbances is included in the final discussion.

2.2 ECOLOGICAL AND GEOMORPHIC ROLE OF WOOD

Over the last 30 years much research has demonstrated the many critical roles that instream wood plays in the maintenance of the ecology, geomorphology and biodiversity of streams and large rivers that either flow through or drain forested watersheds (e.g. Hogan 1986; Harmon et al. 1986; Bisson et al. 1987; Sedell et al. 1988; Naiman et al. 2002; Montgomery and Piegay 2003); however, the majority of this research has been conducted in relatively large streams with widths larger than 5 m (> 3rd order streams on 1:50 000 scale maps) (Hassan et al. 2005a). Although recent interest in small streams has generated a number of synthesis and research contributions focused on small streams (refer to special journal issues with introductions provided by Moore and Richardson 2003; Moore 2005; Danehy and Ice 2007), a limited amount of this research or synthesis has focused on small streams situated in snowmelt dominated hydrologic regimes and forest disturbance regimes dominated by stand replacing wildfires.

In general terms, the ecological and geomorphic roles of wood are numerous and include the following. Instream wood physically alters stream channel morphology by creating areas of local channel scour and deposition (Beschta and Platts 1986; Fausch and Northcote 1992). Habitat for fish and aquatic organisms is created by wood altering channel morphology and through the dissipation of stream energy (Heede, 1972; Keller and Swanson 1979; Bisson et al. 1987; Montgomery et al. 1995). Instream wood also plays critical roles in creating cover for fish (Tschaplinski and Hartman 1983), providing long-term food for aquatic organisms (Dudley and Anderson 1982), retaining transported sediment and organic matter (Bilby and Ward 1989; Nakamura and Swanson 1993), cycling of nutrients (Anderson and Sedell 1979; Bilby and Likens 1980) and provides substrate for aquatic invertebrates (Anderson et al 1984; Sedell et al. 1988).

Physical attributes that distinguish small streams from medium or larger sized streams are a function of the hydrologic characteristics, wood characteristics, degree of terrestrial-aquatic interaction and geomorphic characteristics of the streams (Gurnell et al. 2002; Richardson and Danehy 2007). In comparison to medium or larger streams, small streams have smaller drainage areas and lower stream discharges resulting in lower stream power; therefore, less energy is available to scour stream beds or erode stream banks (Jackson and Sturm 2002; Hassan et al. 2005b). In small streams, wood pieces tend to be stable due to larger piece lengths and diameters in comparison to channel width and depth, with wood mainly controlling hydrology and sediment transfer (Gurnell et al. 2002), typically forcing pools or creating log steps (Montgomery et al. 1995; Curran and Wohl 2003). Bed particle sizes tend to be large in comparison to channel depth (Church 1992) with low storage of fine sediments (MacDonald and Coe 2007). Small streams are also highly coupled to adjacent riparian areas and hillslopes given the high edge to area ratio, with wood abundance and spatial distribution being strongly linked to streamside or upslope disturbances (Gomi et al. 2002; Hassan et al. 2005a; Richardson and Danehy 2007). In the absence of debris flows, wood loads tend to be high with relatively long residence times exceeding, on average, 100 years (Hassan et al. 2005a, Powell 2006). High temporal and spatial variability in wood loads can occur in streams dominated by earth flows, gully erosion or debris flows as a result of wood being transported and redistributed during periods of high disturbance (Hassan et al. 2005a, May 2007). The dynamics of wood also vary geographically due to differences in biogeoclimatic factors that influence, for example, rates of loading and wood decay. Therefore, more research in understanding these processes in different geographic settings is required (Hassan et al. 2005a; May 2007).

2.3 WOOD INPUT AND OUTPUT PROCESSES

The wood budget approach (Benda and Sias 2003) provides a useful framework to describe the processes, controls, storage dynamics and material fluxes of instream wood. The wood budget approach is described as being analogous to studies in sediment budgeting (Benda and Sias 2003; Gurnell et al. 2002), where wood inputs minus wood outputs are equivalent to changes in wood storage. Similar to sediment budgets (Reid and Dunne 1996; Campbell and Church 2003), wood budgets are useful when few or no process measurements are available. Using this approach, Benda and Sias (2003) identified six primary processes that describe the abundance and distribution of instream wood. These input and output processes include episodic forest death, forest growth and chronic mortality, bank erosion, mass wasting, decay and stream transport.

Processes related to the episodic input of wood result from punctuated delivery of wood from stand replacing disturbances associated with catastrophic events such as wildfire, insect epidemics, mass wasting (e.g. debris flows and landslides), flooding or windthrow

(Bragg 2000; Benda and Sias 2003). Chronic mortality occurs at a more regular temporal scale, with the delivery of wood to a stream through the mortality of individual trees resulting from minor disturbances associated with disease, suppression by competition, windthrow and insects, to name a few (Harmon et al. 1986). Bank erosion can be considered to be both a chronic or episodic input depending upon the rate of erosion. Annual migration of channel banks is common in unconfined alluvial stream networks in higher order streams, resulting in chronic supplies of instream wood through undercutting of stream banks; however, large floods can result in significant bank erosion resulting in a punctuated supply of wood in a relatively short period of time (Nakamura et al. 2000). Mass wasting, floods and debris flows can contribute large amounts of wood from hillslopes and upstream channels (Keller and Swanson 1979) with recent research highlighting the significance of wood input from upslope sources as result of debris flows in much of the Pacific Northwest (May and Gresswell 2003; Reeves et al. 2003). The relative importance of each of these input processes is highly variable and depends upon local conditions and stream size (MacDonald and Coe 2007). For example, May and Gresswell (2003) found more than half of the total wood was delivered to 2nd order colluvial streams from slope instability as compared to about 10% of the total wood in 3rd order alluvial streams.

Processes mainly responsible for the output of wood include decay that occurs as result of invertebrate consumption, leaching, physical abrasion and microbial decay (Harmon et al. 1986). The rate of decay is complex and involves the interplay of many biological and physical processes. Decay is controlled by many factors which include climate, tree species (chemical content), piece size (diameter), decay class, position (suspended, on ground, buried, fully submerged), major decomposition process underway (e.g. respiration and leaching or fragmentation), and site conditions (temperature, moisture levels, oxygen and carbon dioxide levels) (Harmon et al. 1986; Golladay and Webster 1988; Sedell et al. 1988). Stream transport, the remaining output (and input to downstream reaches) process, is highly dependent upon channel width in relation to piece length, channel stability, flood intensity, frequency and occurrence of debris flows and riparian forest composition (Harmon et al 1986; Naiman et al. 2002).

To date, the majority of published research has focused on the delivery of wood associated with the chronic mortality and the toppling of individual trees within old growth riparian areas (e.g. Murphy and Koski, 1989; Robison and Beschta 1990; Van Sickle and Gregory 1990). Only two studies (e.g. Bragg 2000; Bend and Sias 2003) have focused on the episodic delivery of wood to streams associated with wildfires or other major stand replacing disturbances. One reason for the limited number of studies focused on the episodic delivery of wood partially stems from the fact that the majority of these wood studies have been conducted in ecosystems that experience relatively infrequent catastrophic disturbances such as wildfires (i.e. old growth forests of the Pacific Northwest). However, the importance of these catastrophic events becomes critical in ecosystems that experience frequent natural disturbance events such as wildfire or epidemic insect infestations characteristic of the southern interior of British Columbia.

2.4 DISTURBANCES AND INSTREAM WOOD

Numerous past studies have focused on the amounts, distribution and geomorphic role of wood in streams, but few of these studies have considered wood explicitly in terms of disturbances (Nakamura and Swanson 2003). Disturbances have been recognized as an important element in maintaining ecological function, complexity and diversity in both forest and aquatic ecosystems (e.g. Resh et al. 1988; Attiwill 1994; Franklin et al. 2002; Bisson et al. 2003); therefore, increased understanding of wood in a disturbance context is critical given the many ecological roles (i.e. structural and functional) provided by wood. Disturbances can affect wood in three main ways (Nakamura and Swanson 2003). First, disturbances can alter the delivery of wood to streams both directly or indirectly. Secondly, disturbances can alter the frequency and magnitude of streamflow and sediment that enters a stream network altering wood transport and quantity. Lastly, and as result of changes in the storage, deposition and transport of wood caused by the first two effects, disturbances can affect the biological and physical components of riparian and aquatic habitat.

The effects of disturbances on wood depend upon the geographic setting across a channel network (Benda and Sias 2003; Nakamura and Swanson 2003; May 2007). Conceptually, a channel network can be stratified into a number of "disturbance process-based segments" (Fetherston et al. 1995, and references cited therein) and this concept has emerged as an important conceptual framework for understanding watershed-level controls on wood input, transport and output processes in coastal regions of North American (e.g. Fetherston et al. 1995; Nakamura and Swanson, 2003; Benda and Sias

2003). Basically, the framework stratifies a watershed into three components (Fetherston et al. 1995; Nakamura and Swanson 2003): (1) debris-flow and avalanche channels characterized by high-gradient, boulder dominated headwater streams, very narrow valley floors and steep, well connected hillslopes; (2) debris-flow channels characterized by gravel bed streams with relatively steep channel gradients; and (3) fluvial channels characterized by low-gradient, sand bed streams and meandering channel patterns. Wood input, transport and output processes vary across these geographic settings and have been described by Keller and Swanson (1979) and Swanson (2003) for streams situated in the Oregon Cascade Range. For example, debris-flow and avalanche channels are dominated by indirect inputs of wood from mass wasting events (e.g. debris flows, gully erosion, snow avalanches) from connected hillslopes and direct wood inputs from mortality (chronic and episodic) of adjacent streamside vegetation. Wood transport and output processes are dominated by physical fragmentation and debris flows. In contrast, fluvial channels are dominated by wood inputs from bank erosion, localized earthflows and floatation of wood from upstream areas with wood transport and output being dominated by floatation, decomposition and physical fragmentation wood. Further research is required to determine the applicability of this conceptual framework in watersheds situated in the interior of British Columbia that are dominated by high plateaus and relatively low gradient streams.

The River Continuum Concept (Vannote et al. 1980) can also been used to provide a basic conceptual framework to describe the effect disturbances have on the storage dynamics and fluxes of wood within a watershed context. In its simplest form, the River

Continuum Concept describes the stream network as a linear gradient or continuum with processes occurring in the headwaters being directly linked to downstream, higher order reaches. Based on the River Continuum Concept, headwater streams are strongly influenced by adjacent riparian areas and allochthonous inputs supplying the majority of organic matter to the stream with downstream, higher order streams being less dependant on external inputs of organic matter with most of the organic material transported from upstream sources.

It is important to highlight that the River Continuum Concept provides a linear perspective of the stream network and that many discontinuities in physical and biological processes can occur both spatially and temporally within a watershed (e.g. Montgomery 1999; Benda et al. 2004; Kiffney et al. 2006). For example, tributary junctions have been shown to be active areas of disturbances due to debris flows (Benda et al. 2003) and have been shown to be areas of higher biological productivity, and habitat complexity with wood abundance peaking at or below tributary junctions (Kiffney et al. 2006). These discontinuities along the channel network have challenged the past linear thinking of the River Continuum Concept and a more network oriented view of streams has emerged (e.g. Montgomery 1999; Gomi et al. 2002; Benda et al. 2004).

Although these frameworks have been important in the description of wood processes in headwater streams in the context of larger fluvial streams or rivers (e.g. Benda and Sias 2003; Nakamura and Swanson 2003; Hassan et al. 2005a; May 2007) one obvious and underlying assumption is the role that mass wasting events play in dominating wood input, transport and output processes. As pointed out by May (2007) this framework does not address wood in small streams and associated with other disturbance regimes that are not dominated by mass wasting events. Little is known about the spatial extent of these streams and whether these channels represent “relic” channel conditions from past climate and geomorphic processes (May 2007).

2.5 TEMPORAL DYNAMICS OF WOOD AND WILDFIRE DISTURBANCES

The temporal dynamics of instream wood associated with major stand replacing wildfire disturbances have been identified as a research gap (Bragg 2000; Naiman et al. 2002; Bisson et al. 2003; Benda and Sias 2003). To date, the majority of published research has focused on the quantity and characteristics of instream wood present within old-growth forests with the majority of these studies completed in the coastal regions of the Pacific Northwest (e.g. Bilby and Likens 1980; Lienkaemper and Swanson 1987; Hogan 1987; Bilby and Ward 1989; Ralph et al. 1994; Woodsmith and Buffington 1996; Gomi et al. 2003). Many of these studies have taken a relatively static perspective on instream wood loading, with comparisons limited to streams flowing through old-growth forests versus streams flowing through areas that had been clearcut harvested and/or cleaned of wood. Although these studies have provided important insight into the effects associated with these practices, these studies have been limited to relatively short-term field measurements limited to one point in time resulting in a limited understanding of the long-term temporal dynamics of instream wood (Benda and Sias 2003; Hedman et al 1996).

In stream environments, overall wood storage is a function of the input (i.e. recruitment) and output (i.e. depletion) of instream wood. The long-term trend in wood storage associated with a major wildfire disturbance has been hypothesized to follow a U-shaped pattern (Harmon et al. 1986) in association with the episodic delivery of dead trees and through succession of the regenerating forest stand. The highest amounts of instream wood storage are hypothesized to occur within approximately 20-50 years after a major wildfire disturbance due to the episodic delivery of wood from the toppling of dead trees, with the lowest instream wood storage associated with the regeneration of young riparian forest stands approximately 60-100 years after the wildfire disturbance (Figure 2.1). The low storage occurs as result of attrition of existing instream wood and low input of wood to the stream channel in association with regrowth of the riparian forest stand. Once the forest stand matures and approaches an old growth condition an increased delivery of wood occurs due to individual tree mortality caused by competition and small-scale disturbances (e.g. windthrow, disease or insects). In old growth conditions wood storage has been hypothesized to approach a steady-state where the wood inputs are equivalent to the outputs (Harmon et al. 1986, Murphy and Koski 1989).

Although few field studies have specifically focused on the temporal dynamics of wood storage in stream environments, the influence of wildfire on the temporal dynamics of wood storage in terrestrial environments (commonly termed coarse woody debris or CWD) has received more attention in the literature (e.g. Harmon et al. 1986, Spies et al. 1988; Feller 2003; Wei et al. 2003; Delong et al. 2003). These terrestrial wood studies provide a useful reference in explaining the potential temporal patterns that wood may follow in stream environments. In terrestrial environments there are several trends in which the quantity of wood can vary in association with forest age, forest stand dynamics and in response to natural disturbances (Feller 2003). In forest types similar to the south-central interior of British Columbia, Brown and See (1981) identified three different temporal patterns of wood loading in different lodgepole pine (*Pinus contorta*) forests in western Montana and Northern Idaho. The first pattern involved an increasing amount of wood as the forest aged, with peak loads occurring in old-growth forest stands. The second trend followed an inverse U-shaped pattern with maximum wood loads occurring in mature forest stands 110 to 160 years old. The third trend followed a U-shaped pattern with maximum wood loads being observed in the youngest and oldest stands. In another study conducted in the northern portion of Rocky Mountains of British Columbia, no relation was found between wood loads and the time since the last major disturbance (Delong et al. 2003). In the literature a U-shaped trend in wood loading appears to be the most common (e.g. Spies et al. 1988; Sturtevant et al. 1997; Clark et al. 1998; Duvall and Grigal 1999). The diversity in temporal trends observed in the literature is linked to the forest stand dynamics and the different successional development pathways that forests of different composition and structure can follow (Oliver and Larson 1996; Franklin et al. 2002).

2.6 TEMPORAL DYNAMICS OF WOOD AND STREAMSIDE CLEARCUT HARVESTING

Streamside clearcutting has been hypothesized to affect instream wood dynamics differently than wildfires, with an initial decline in instream wood supply and storage occurring subsequent to harvesting (Figure 2.1). However, field research from the coastal Pacific Northwest has found both increases and decreases in the number and volume of wood pieces after logging (Hassan et al. 2005a). Reduced instream wood occurring shortly (<30 years) after forest harvesting was most commonly associated with excessive stream cleaning and increased breakage and mobility of instream wood. Increased instream wood was commonly associated with the introduction of logging slash directly after logging. Few of these studies have been able to study changes in wood loads beyond 40 years given the relatively recent history of industrial logging in this region.

Instream wood amounts based on published and unpublished research conducted in similar forest types to those found in the interior British Columbia also show no consistent pattern in association with forest harvesting. For example, McGreer and Schult (1999) compared several data sets from streams flowing through unmanaged and managed riparian forests in the interior Columbia River Basin (includes Eastern Washington, Eastern Oregon, Idaho and Montana) of the U.S. and North Central Colorado. Statistically significant reductions in wood frequency associated with forest harvesting were identified in one out of six of the compared data sets, with reduced wood volumes identified in two out of four of the compared data sets (McGreer and Schult

1999). No increases in wood volumes were identified. Reductions in wood loadings are highly dependent upon a number of factors that include the size of the stream channel, inherent stability (e.g. channel widening) of the stream channel and the occurrence of landslides or debris flows that transport large amounts of wood (Beschta 1984, Hogan 1986, Gomi et al. 2002). These conflicting findings are also related to differences in management guidelines and practices (e.g. slash removal versus non-removal), size distribution of wood, and the time since the occurrence of logging (Hassan et al. 2005a).

Disturbances associated with forest management activities can affect the delivery, quantity and transport of wood to streams in a number of ways. Loss of streamside trees from streamside clearcut harvesting results in reduced availability of wood for recruitment to streams (Murphy and Koski 1989). Increased magnitude and/or altered frequency of mass wasting associated with forest harvesting and roads can result in deposition, scour or increased mobility of wood within a stream network (Hogan 1986; Gomi et al. 2003). Increases in wood loads can also occur from logging slash entering streams (Millard 2000; Jackson et al. 2001; Gomi et al. 2003). Reduction in wood loads can occur from removal of wood due to “stream cleaning” (Bilby 1984).

2.7 SPATIAL DISTRIBUTION OF WOOD

In small streams, wood tends to lie where it fell, creating a dispersed, random pattern of wood with increased aggregation and more clumped pattern of wood occurring downstream in higher stream orders (Bisson et al. 1987); however, this general pattern can vary depending upon several factors. These factors include source areas that are spatially discrete versus dispersed along a channel network; wood transport capacities that are low versus high; channel profile characteristics that determine whether wood will be trapped, deposited or transported; and type, frequency and magnitude of disturbance (Swanson 2003). Swanson (2003) categorized the arrangement/pattern of wood based on four major types of controls: (1) discrete-source-patch control of pattern, (2) trapping-site control of pattern, (3) transport control of pattern and (4) dispersed-source control of pattern. Discrete-source-patch control includes channel profiles that are dominated by discrete source areas of wood where limited transport capacities are shorter than the distance between source areas, resulting in a clumped pattern of wood. Trapping-site control occurs in channels that are dominated by long transport distances relative to source areas, with well defined discrete areas that trap wood resulting in a clumped pattern of wood. Transport control occurs in channels characterized by long transport distances with no discrete trapping areas, resulting in a randomly dispersed pattern of wood. Dispersed source control pattern occurs in channels that are dominated by dispersed sources of wood and low transport capacities, creating a random distribution of wood. The first three pattern controls are typically dominated by debris flow transport of wood.

2.8 CHANNEL MORPHOLOGY, WILDFIRE DISTURBANCES AND FOREST HARVESTING

Disturbances such as forest harvesting and wildfires have the potential to alter sediment, streamflow and wood inputs in a stream system that in turn can result in changes in channel morphology (Montgomery and Buffington 1997; Gresswell 1999). At the reach scale, numerous structural characteristics of channels can be altered, including channel width, channel depth, bed material, channel habitat characteristics (e.g. pool volume, pool depth, and pool-riffle frequency), bank stability and height of channel steps, to name a few (MacDonald et al. 1991; Bilby and Ward 1991; Jackson and Sturm 2002)

Changes in the character, volume and frequency of sediment inputs can occur from increased frequency of mass wasting or surface erosion from forest management activities or wildfire (Wondzell and King 2003; Benda et al. 2005). For example, forest roads and timber harvesting in steep terrain have been shown to increase the frequency and magnitudes of landslides (Sidle et al. 1985). Also, wildfires have been shown to cause debris flows (Jordan et al. 2004; VanDine et al. 2005). Direct influences on channel morphology from mass wasting are highly dependent upon the level of connection between the hillslope, valley flat and stream channel (BC Ministry of Forests 1996, Hassan et al. 2005b).

Channel morphology changes associated with changes in streamflow, most particularly increased peak flows as a result of clearcut harvesting and roads, are one of the most debated issues in forest hydrology. In the absence of other factors (e.g. altered sediment or loss of riparian vegetation) there currently is a lack of evidence that forest harvesting activities have changed channel morphology as result of altered streamflows (Beschta and Platts 1986; Reiter and Beschta 1995); however, the relative response to changes in streamflow depends upon the overall stability and sensitivity of channels (Montgomery and Buffington 1997). Wildfires can also alter streamflows through loss of vegetation, creation of water repellent soils and reduced canopy interception (Wondzell and King 2003).

Research over the last thirty years has shown that forest harvesting activities and wildfire can change the size and abundance of wood supply by altering the recruitment, distribution and transport of wood in streams (Hogan 1986; Hassan et al. 2005a; Zelt and Wohl 2004). As already discussed wood can play many geomorphic roles within a stream channel; therefore, any alteration to wood supply could negatively change channel morphology. In the literature the relative response of channels to change associated with forest harvesting activities is quite variable (Robison 1997; Mellina and Hinch unpublished data) and depends upon several factors that include the sensitivity of channels to change; local site conditions (e.g. climate, soils, surficial geology and geomorphology); management history (stream cleaning versus no slash removal; type of logging); riparian management (buffers versus no buffers); extent of logging, hillslope stability and hillslope coupling to stream channels (Hassan et al. 2005b; Benda et al. 2005; Mellina and Hinch unpublished data). Similar factors also determine the response of channels to wildfires (e.g. Gresswell 1999; Benda et al. 2003; Zelt and Wohl 2003). Factors include fire severity and extent, local site conditions, hillslope stability and hillslope coupling. To date, no studies have compared channel responses between streamside clearcut harvesting and wildfire.

2.9 CONCLUSION

Although a large body of knowledge exists regarding the importance of wood in streams, many knowledge gaps still exist in regards to small streams, especially since much of the small stream research has been conducted in relatively steep, well coupled streams, often dominated by mass wasting disturbance processes. In reflecting on the significant knowledge gaps that still exist a question posed by Lisle (2002) puts these gaps in context: "How much dead wood in stream channels is enough?" In a forest management context this question becomes particularly important since forest managers are trying to seek an appropriate balance between the economic value of riparian trees and its ecological contributions. At a first glance this question may seem rather simple to answer given the many well known ecological roles wood plays within streams but, in reality, this question is not so simple to address. Addressing this question is particularly important in the context of small streams since the majority of streams in a watershed flow directly through large areas of economically important timber supply. In attempting to address this question and in order to improve forest management decisions, Lisle (2002) suggested that three kinds of information are still required: a clearer understanding of the ecological role of wood in forest streams; a clearer understanding of the processes, controls and longevity of wood storage dynamics and fluxes; and a clearer understanding of wood loads in managed in comparison to unmanaged, natural conditions.

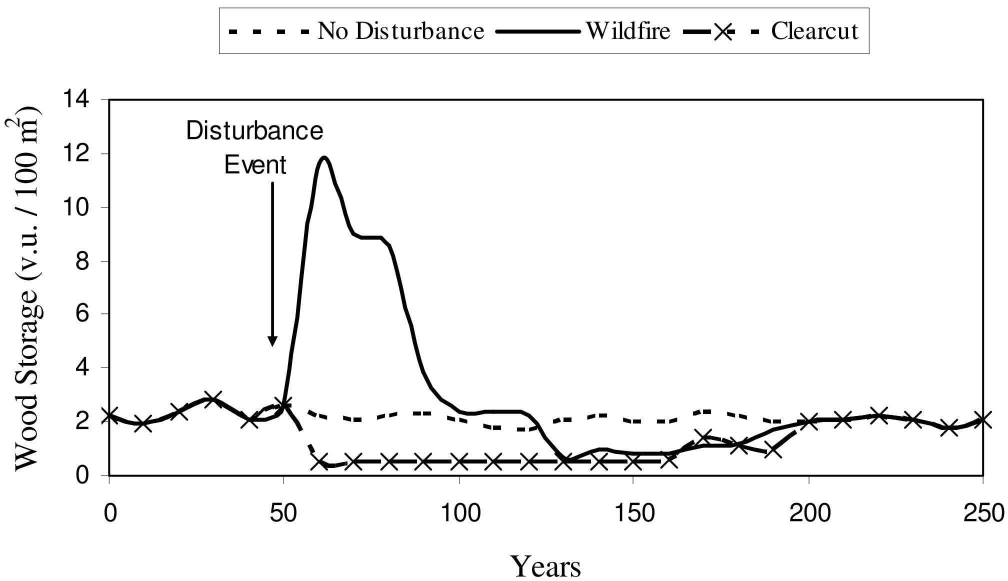


Figure 2.1. Simulated instream wood storage associated with various disturbances. Units of storage labeled v.u. as arbitrary volume units. (adapted from Bragg 2000 and Benda and Sias 2003).

CHAPTER 3

STUDY AREA AND DRAINAGE BASIN COMPARISON

3.1 STUDY AREA

This study was conducted in the Okanagan Highlands and Thompson Plateau in south-central British Columbia within a 100 km radius of the city of Kelowna (43^{o}10'N, 79^{o}55'W) (Figure 3.1 and 3.2). The Okanagan Highlands and Thompson Plateau range in elevation from approximately 1000 m to over 1800 m and lie within the rain shadow east of the Cascade Mountain Range and west of the Monashee Mountains. Mean annual precipitation ranges from 400 mm to over 1000 mm, with the majority falling as snow above 1200 m in the winter months. Mean annual temperatures range from 1.7 to 4.7°C. Annual streamflow in this area is typical of snow-dominated hydrologic regimes, with peak runoff occurring between April and mid July, primarily from melting snowpacks situated above 1200 m (Canada-British Columbia Okanagan Basin Agreement 1974).

The Okanagan Highlands and Thompson Plateau are characterized by rolling terrain with few slopes greater than 60% (Figure 3.3). Landslides and debris flows are relatively uncommon, except along a few mainstem stream channels that are deeply incised in the morainal blanket. Small streams generally have gradients less than 15%, and have boulder/cobble channel beds and banks (Figure 3.4 to Figure 3.7). Surficial deposits in the area include thick, unconsolidated deposits of glacial drift covering much of the bedrock in the area, with numerous bedrock outcrops and thin morainal veneers (Roed 1995). Most soils in the area are moderately well to well drained and are classified as

Humo-Ferric Podzols. Humus forms are generally Mors (Hemimors, Hemihumimors, and Humimors), and range from 3 to 10 cm in thickness (Meidinger and Pojar 1991).

Forest ecosystems adjacent to the study streams area are dominated by Montane-Spruce (MS) and Engelmann Spruce Subalpine-Fir (ESSF) forest ecosystems (Meidinger and Pojar 1991). Riparian forest stands situated within the study area consisted of mixed stands of lodgepole pine (*Pinus contorta*), subalpine fir *(Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) with minor components of Douglas-fir (*Pseudotsuga menziesii*). Lodgepole pine was the leading species at 50% of the study sites with only one site being solely occupied by lodgepole pine. Subalpine fir (26%) and Engelmann spruce (24%) were the leading species at the remaining sites (Table 3.1). Deciduous trees such as trembling aspen (*Populus tremuloides*) and cottonwood (*Populus balsamifera*) are present but are not a significant component of these riparian stands. Forest ecosystems within this area are generally associated with frequent stand-replacing wildfire events, resulting in a landscape characterized by a mosaic of single cohort (even-aged) stands (BC Ministry of Forests 1995). Stand replacing forest fires occur at mean return intervals of 45 to 149 years in the biogeoclimatic zones and subzones that were included in this study (B.C. Ministry of Forests 1995b, Wong et al. 2003).

3.2 COMPARISON OF STUDY STREAM DRAINAGE BASINS

A total of 38 study streams with various disturbance histories or stand development stages were evaluated in this study. Evaluations included measurements of instream wood volume, abundance, characteristics of wood and channel morphology. The measurement methods and grouping of the 38 study streams are discussed in detail in subsequent chapters; however, an overview of the basin characteristics for each study stream is provided here (Table 3.2).

Cluster analysis was applied to characteristics of the drainage basins for the study streams, to ensure that the study streams came from a homogeneous population of drainage basins having similar geomorphic setting and morphology. Similarity of drainage basin characteristics is important to reduce sources of variation and to ensure the study streams respond to disturbances in a similar manner (Hogan et al. 1998; Trainor and Church 2003). Comparison of various morphometric characteristics for the drainage basin was assessed using the approach developed by Cheong (1996) and later modified by Trainor (2001). The morphometric parameters used in the analysis included drainage basin area (km^2), mean basin elevation (m), lake area (km^2), valley flat area (km^2), steepland area (km^2), drainage density (km/ km^2) and average basin gradient (m/m). All of these morphometric parameters were calculated using ESRI ArcGIS and ArcInfo (version 8.3) and various data sources (1:20,000 TRIM I/II Water features, 1:20,000 TRIM I/II Digital Elevation Model, 1:20,000 TRIM I/II Contours, 1:20,000 VRI – Vegetation Resource Inventory (Forest Cover Information), 1:50,000 Watershed Atlas, Major Watershed Basins, Watershed Sub-basins, Stream Network and point locations of study streams).

Cluster analysis using the centroid method was then used to measure dissimilarity between the study stream basins. The centroid method calculates the distance between two clusters using the squared Euclidean distance between their means. Also the data were standardized using the mean and standard deviation for each parameter. A scree plot showing the distance between clusters was then used to evaluate the similarity of drainage basins (Figure 3.8). Natural breaks in the scree plot were used to identify the number of clusters. Based upon this information three clusters were identified between the 38 study stream basins with approximately 95% of the study streams associated with the same cluster (Table 3.3). The remaining two study streams (GOLD1 and STER1) were in unique clusters with the GOLD1 study basin having a higher area of steep terrain as compared to the other study basins, and the STER1 study basin having a higher area of lakes. Although these two streams were found to be dissimilar to the other study basins they were still included in this study, especially since the relative percentage of drainage area influenced by steepland or lakes was quite small (<5%).

Table 3.1. Riparian forest stand composition, density and basal area/hectare for the 38 study streams for all trees greater than 10 cm dbh.

Study Stream	Species Composition (%)			Forest Cover Type	Number of Stems/Hectare	Basal Area/ Hectare (m^2/ha)
	Pl	Sx	Bl			
240CRK	77	12	12	Pl(SxBL)	900	39
BEAKUPPER	32	68	0	SxPl	900	85
CANTRIB1*	52	35	13	PlSx(Bl)	1000	37
CANYON*	53	16	32	PlBl(Sx)	950	26
CHRIS1**	10	30	60	BlSx(Pl)	450	68
COLDWATERTRIB	73	27	0	PlSx	550	38
CORTRIB	70	19	11	Pl(SxBl)	1550	45
COTTON1	84	0	16	Pl(Bl)	1100	48
CRESTRIB1**	64	36	0	PlSx	1100	48
DARLEY	7	53	40	SxBl(Pl)	550	39
DOME1	36	14	50	BlPl(Sx)	950	59
DOME2	28	22	50	BlPl(Sx)	1400	85
ELLIS	46	27	27	PlSxBl	1300	32
GOLD1**	61	39	0	Pl(Sx)	700	34
HIDDEN*	37	50	13	SxPl(Bl)	750	17
LAMBLY1**	60	40	0	PlSx	450	51
LAMBLY2**	53	47	0	PlSx	600	58
LOWERCORP	23	36	41	BlSx(Pl)	900	56
MUNCRK1	8	42	50	BlSx(Pl)	1050	61
MUNCRK2	78	19	3	Pl(SxBl)	1300	39
NICTRIB1	73	27	0	PlSx	550	32
PASAYTEN1*	20	80	0	Sx(Pl)	500	31
PASAYTEN2*	20	80	0	Sx(Pl)	550	62
PEACH1**	100	0	0	Pl	300	22
PEACH2**	98	0	2	Pl(Bl)	1200	85
PENNASK	36	50	14	SxPl(Bl)	1400	64
REED1	0	29	71	BlSx	700	28
SEL1	0	20	80	BlSx	250	24
STER1	7	45	48	BlSx(Pl)	1100	34
SUN1	0	30	70	BlSx	1000	64
SUN2	45	12	43	PlBl(Sx)	1950	73
TERRACE1**	54	46	0	PlSx	400	48
UNTRT1**	40	29	31	PlBlSx	450	44
UWKRAB1**	80	20	0	PlSx	700	70
UWKRAB2**	41	52	7	SxPl(Bl)	450	59
UWKRAB3**	33	53	14	SxPl(Bl)	750	89
UWKTRIB1	0	27	73	BlSx	600	29
VENTURI	36	57	7	SxPl(Bl)	750	67

Species Symbols: Pl = *Pinus contorta*, Sx = *Picea engelmannii* and Bl = *Abies lasiocarpa*
Forest Cover Type – species are listed in their order of predominance. Major species are listed first, followed by minor species in brackets (i.e. <25% composition).
*denotes wildfire sites with stand characteristics based on predisturbance stand conditions
**denotes clearcut harvest sites with stand characteristics based on predisturbance stand conditions

Table 3.2. Drainage basin characteristics for the 38 study streams. Note: Detailed comparisons of basin characteristics by stand development stage and disturbance category are included in Chapters 4 and 5.

Study Stream	Basin Area (km^2)	Mean Basin Elev. (m)	Area in Lakes (km^2)	Area of Valley Flat* (km^2)	Area of Steepland* (km^2)	Drainage Density (km/km^2)	Mean Gradient of Basin (m/m)	BEC Zone and Subzone
240CRK	3.53	1820	0.00	0.47	0.06	1.92	0.04	ESSFdc 1
BEAKUPPER	7.86	1530	0.10	1.95	0.00	1.70	0.03	MSdm 2
CANTRIB1	3.03	1795	0.00	0.95	0.11	1.90	0.05	MSdm 1
CANYON	3.20	1815	0.00	0.43	0.00	1.69	0.05	MSdm 1
CHRIS1	3.96	1614	0.04	0.74	0.24	2.63	0.04	MSdm 2
COLDWATERTRIB	6.83	1410	0.00	0.30	0.12	2.53	0.12	MSdm 1
CORTRIB	0.97	1864	0.00	0.01	0.00	2.89	0.12	ESSFdc 1
COTTON1	1.79	1608	0.00	0.03	0.00	2.83	0.11	MSdm 2
CRESTRIB1	6.34	1643	0.00	0.76	0.00	1.89	0.16	MSdm 2
DARLEY	6.34	1558	0.00	1.70	0.00	1.70	0.06	MSdm 1
DOME1	5.17	1609	0.01	2.02	0.00	1.91	0.07	ESSFdc 2
DOME2	9.42	1653	0.00	2.78	0.00	2.54	0.05	ESSFxc
ELLIS	15.82	1699	0.00	2.68	0.00	1.55	0.06	MSdm 1
GOLD1	12.56	1575	0.02	2.90	0.51	2.67	0.05	MSxk
HIDDEN	1.75	1836	0.00	0.13	0.00	1.97	0.07	ESSFxc
LAMBLY1	2.67	1646	0.00	0.45	0.00	3.48	0.10	ESSFdc 2
LAMBLY2	0.65	1573	0.00	0.16	0.00	2.08	0.11	ESSFdc 2
LOWERCORP	4.05	1816	0.01	0.70	0.01	1.52	0.05	ESSFdc 1
MUNCRK1	2.31	1806	0.00	0.13	0.00	0.76	0.14	ESSFdc 1
MUNCRK2	7.18	1796	0.00	1.44	0.00	0.62	0.04	ESSFdc 1
NICTRIB1	2.50	1502	0.00	0.38	0.00	2.37	0.04	MSxk
PASAYTEN1	8.37	1860	0.00	0.21	0.05	1.51	0.08	ESSFdc 2
PASAYTEN2	8.14	1873	0.00	0.19	0.05	1.57	0.08	ESSFdc 2
PEACH1	1.66	1447	0.00	0.19	0.05	2.17	0.05	MSdm 2
PEACH2	3.50	1562	0.00	0.71	0.00	1.30	0.09	MSdm 2
PENNASK	11.99	1807	0.02	3.59	0.00	1.83	0.01	MSdm 2
REED1	3.73	1783	0.05	1.05	0.00	0.82	0.08	ESSFdc 1
SEL1	3.16	1599	0.00	1.24	0.01	1.86	0.07	MSdm 1
STER1	14.20	1715	0.19	2.86	0.11	1.96	0.05	MSdm 1
SUN1	4.37	1593	0.00	0.65	0.06	2.02	0.09	MSdm 2
SUN2	4.85	1569	0.00	0.83	0.06	2.00	0.08	MSdm 2
TERRACE1	3.84	1563	0.01	1.17	0.00	3.04	0.05	MSdm 2
UNTRT1	3.08	1696	0.01	0.75	0.00	1.50	0.04	MSdm 2
UWKRAB1	8.68	1550	0.01	1.11	0.00	2.10	0.03	ESSFdc 1
UWKRAB2	5.71	1575	0.00	0.80	0.00	1.19	0.04	ESSFdc 1
UWKRAB3	5.88	1573	0.00	0.87	0.00	1.20	0.03	ESSFdc 1
UWKTRIB1	0.81	1658	0.00	0.13	0.00	2.03	0.08	ESSFxc
VENTURI	7.42	1479	0.00	1.25	0.17	1.17	0.08	MSxk

* Area of Valley Flat was defined as areas with slopes < 7% and Area of Steepland was defined as areas with slopes > 60% using a 25 m x 25 m grid size

Table 3.3. Proportion and number of clusters of drainage basins when 3 clusters are used.

Cluster Level	Count	Proportion of Study Stream Basins (%)
1	1	2.5
2	1	2.5
3	36	95.0
Total	38	100

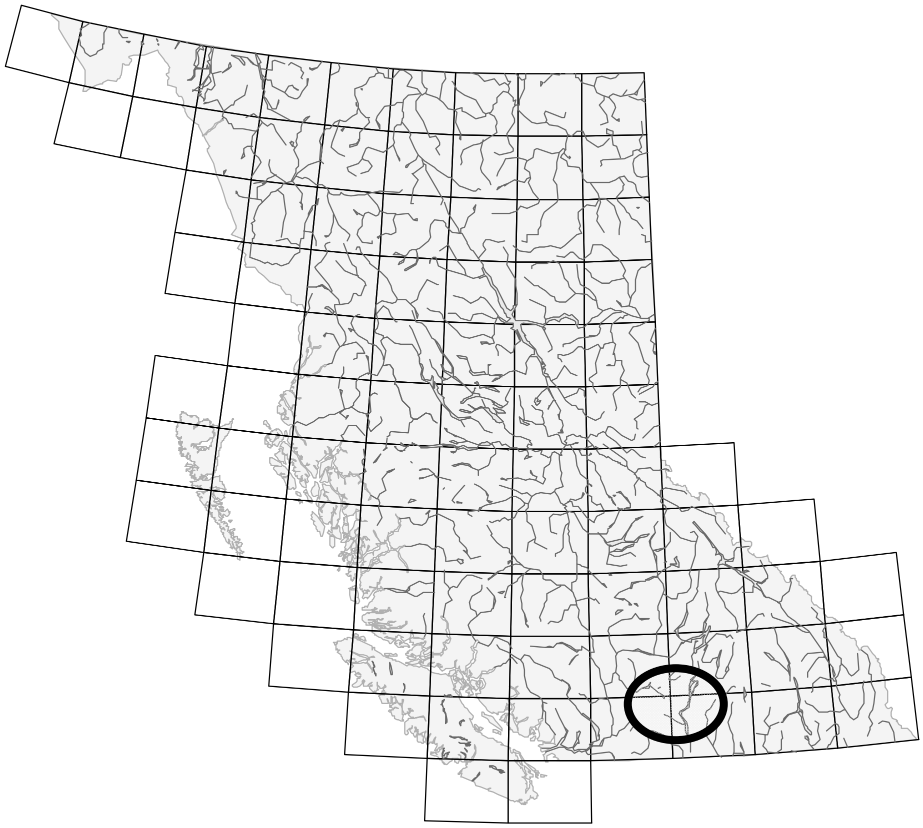


Figure 3.1. Location of study area within the south-central interior of British Columbia.

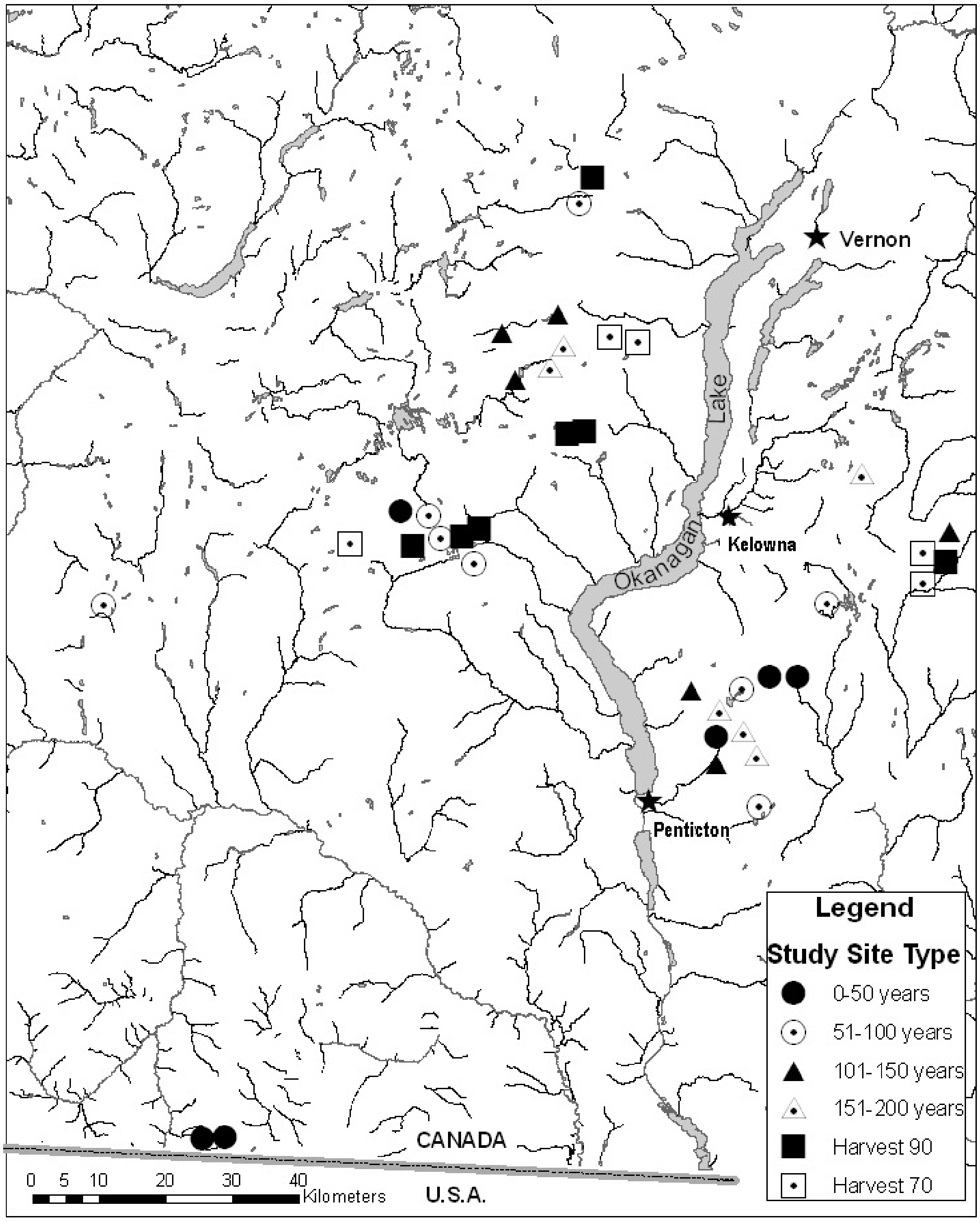


Figure 3.2. General location of 38 study streams used in this study, south-central British Columbia. Symbols refer to riparian tree age or time since disturbance (e.g. Harvest 90 denotes streamside clearcut sites that occurred in the 1990's and Harvest 70 denotes streamside clearcut sites that occurred in the 1960s to 1970s).

Figure 3.3. Overview of watershed with rolling terrain that is typical of the Okanagan Highlands and Thompson Plateau study area.

Figure 3.4. Photo of study stream with an average bankfull width of 3.4 m, a gradient of 6% and a riparian tree age of 49 years subsequent to wildfire.

Figure 3.5. Photo of study stream with an average bankfull width 1.4 m, a gradient of 3%, and a riparian tree age of 115 years.

Figure 3.6. Photo showing riparian area of study stream disturbed by wildfire 32 years ago.

Figure 3.7. Photo showing typical example of a streamside clearcut harvested stream (logging date = 1993).

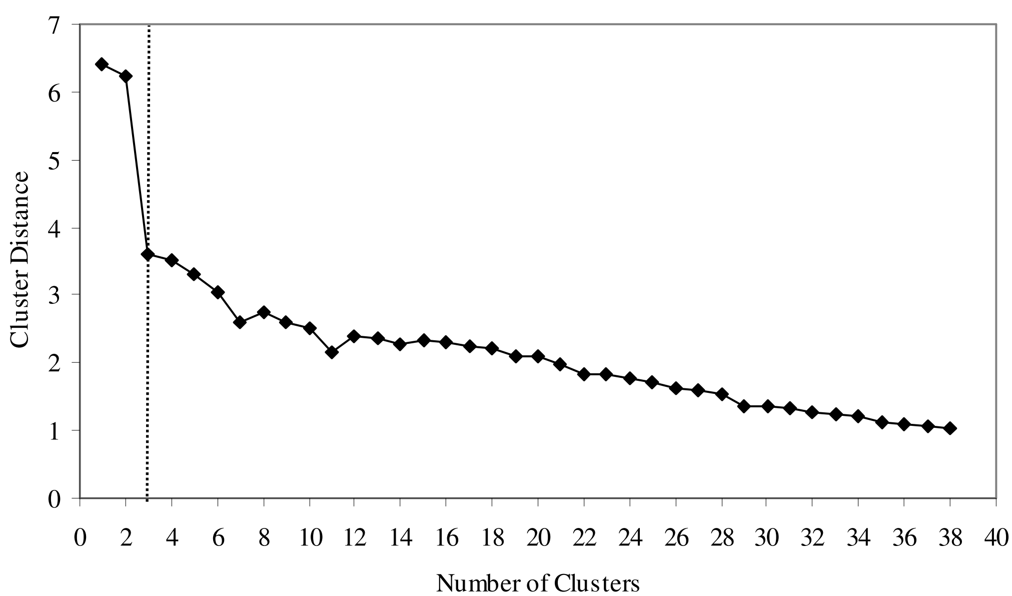


Figure 3.8. Scree plot showing the number of clusters and the distance between clusters (Vertical dashed line indicates break where distances increase suddenly and suggests a natural cutting point to determine the number of clusters).

CHAPTER 4

CHRONOSEQUENCE OF INSTREAM WOOD IN RELATION TO WILDFIRE DISTURBANCES AND STAND DEVELOPMENT STAGES

4.1 INTRODUCTION

The temporal dynamics of instream wood associated with major disturbances such as stand replacing wildfire have been identified as a research gap (Bragg 2000; Naiman et al. 2002; Bisson et al. 2003; Benda and Sias 2003). The long-term trend in wood storage associated with a major wildfire disturbance has been hypothesized or modelled to follow U-shaped pattern (Harmon et al. 1986; Bragg 2000; Benda and Sias 2003). The highest amounts of instream wood storage are hypothesized to occur approximately 20-50 years following a major wildfire disturbance due to the episodic delivery of wood from the toppling of dead trees. The lowest instream wood storage occurs approximately 60-100 years after the wildfire disturbance as result of attrition of existing instream wood and low input of wood to the stream channel in association with regrowth of the riparian forest stand. Once the forest stand matures and approaches an old growth condition, individual tree mortality caused by competition and minor disturbances (e.g. windthrow, disease or insects) increases delivery of wood to the channel. In old growth conditions, wood storage has been hypothesized to approach a steady-state where the wood inputs are equivalent to the outputs (Harmon et al. 1986, Murphy and Koski 1989). However, empirical support for those modeling results is lacking.

The general objective of this study was to document using field surveys the temporal evolution of instream wood following a wildfire. The specific objectives of this chapter included: (1) evaluation of the temporal dynamics of instream wood quantity (i.e. volume and number) in small streams in south-central interior of British Columbia in relation to riparian stand age and four stand development stages; (2) evaluation of several instream wood characteristics (i.e. size, orientation, position, decay state and input source) in relation to riparian stand age and stand development stage; (3) determination of the depletion rate and persistence of instream wood inputs from pre-disturbance riparian forest stand following a major wildfire disturbance.

The analysis focused on the following primary hypotheses:

1. The number and volume of wood pieces following a major stand replacing disturbance will exhibit a U-shaped pattern in time as proposed by Bragg (2000) and Benda and Sias (2003)
2. Wood characteristics (i.e. size, orientation, position, decay, and input) change in relation to stand development stage and the time since the last major stand replacing wildfire disturbance. Hypothesized changes include:
    a. A decrease in wood piece size in association with earlier stand development stages (e.g. stem initiation, stem exclusion) followed by an increase in piece size associated with attrition of larger trees in the older stand development stages (e.g. understory re-initiation, old growth transition phase);

b. An increase in wood volume oriented parallel to streamflow following wildfire disturbances due to increased mobility of wood associated with increased channel instability and streamflows;

c. A decrease in wood volume spanning stream channels in relation to time since the last major wildfire disturbance;

d. An increase in wood volume in an advanced state of decay in relation to time since the last stand replacing disturbance; and,

e. A variation in wood input sources in relation to time with a larger proportion of wood inputs related to fire in the youngest stand development stages and increased wood inputs associated with chronic mortality occurring in the later stages of stand development.

3. In the absence of major stream channel disturbances such as debris flows wood should persist in small streams for approximately 100 years as suggested by Hassan et al. (2005a).

4.2 Methods

4.2.1 Sample Streams and Study Design

A chronosequence approach (i.e. space for time substitution) that has also been utilized to identify trends in terrestrial wood (e.g. Spies et al. 1988; Wei et al. 1997; Sturtevant et al. 1997; Clark et al. 1998; Duvall and Grigal 1999) was employed in this study to evaluate how the quantity and characteristics of instream wood change in relation to riparian stand age. In the absence of long-term studies (e.g. >100 years), chronosequence studies are useful in providing important insights into long-term ecosystem processes (Cole and Van Meigroet, 1989). In spite of its wide application, however, the chronosequence approach has some limitations, including 1) all study sites in a chronosequence should be from the same origin; and 2) similar environmental factors should have influenced the development of the chronosequence.

A total of 26 small (< 3rd order on 1:30,000 scale forest cover maps) stream reaches with bankfull widths less than 5 m (25 of the 26 study streams had widths less than 4 m) were selected within the Okanagan Highland and Thompson Plateau study area (refer to Chapter 3). Potential sample streams were first identified and classified by stream order on 1:30,000 scale forest cover maps. The potential sites were then assessed on the ground and selected if the site met the following criteria: (1) reach length > 150 m, (2) continuous, defined banks and alluvial sediment beds, and (3) logging never occurred in the riparian stand. All sampling occurred in the months of July to October during low streamflow conditions. To reduce geomorphic sources of variation, only stream channels with similar geomorphic settings (e.g. gradient, channel confinement, basin area) were studied since the emphasis of this study was on the trends associated with riparian stand age. The assumption of similar geomorphic settings was tested as part of the data analysis in this chapter.

Historic airphotos from 1938 to 1998 were also used to evaluate the disturbance histories of the riparian forest stands adjacent to the study streams. It was assumed that all riparian forest stands had evolved from major disturbances of similar fire severity. Based upon the observed forest stand conditions (riparian plots) and historic airphotos this assumption seems to be reasonable for the recently (<100 years) disturbed study streams. For example, these streams were characterized by even-aged forest stands, snag densities and forest cover patterns characteristic of stand replacing wildfires. The older riparian stands were more difficult to characterize and may have undergone alternative stand initiating (major disturbances) and stand maintaining events (minor disturbances) (refer to section 4.4.1 for further discussion).

4.2.2 Field Methods

In each of the 26 study streams, a representative section of stream of 150 m in length was sampled. The section length was based on the standardized approach developed by the United States Environmental Protection Agency's Environmental Monitoring and Assessment Program (Kaufmann and Robison 1998) with study reach lengths well exceeding the required 40× the average wetted width. Although recent literature has suggested that longer sample lengths (>1.5 km) are required to characterize wood volume and abundance (e.g. Benda et al. 2003; Young et al. 2006) it is important to highlight that those studies were focused on characterizing the wood volume and abundance in an entire stream network, where the spatial distribution of wood can be quite heterogeneous due to transport processes that influence the arrangement of wood within a watershed (refer to Chapter 2 regarding spatial arrangement of wood). In this study, a random spatial distribution with low wood transport capacities was observed (refer to Chapter 7); therefore, wood loads were assumed to be directly influenced by lateral recruitment of wood with the influence of riparian stand conditions considered homogeneous along each study reach. To reduce sampling variability, only streams with similar hydrologic regime, stream order, valley form and bankfull width were used. A further issue in sampling small streams is that the study reach lengths are often physically limited by the uppermost extent of streams, at which point streams become undefined. Similarly, in a downstream direction, the heterogeneity of larger streams increases due to larger channel widths, increased stream power, changes in riparian vegetation and variations in the interplay of the various wood input and output processes. Also, forest cover and structure associated with disturbances such as wildfire or clearcutting may only span relatively short distances along the stream channel. Given these factors and the fact that the primary focus of this research was to assess the influence of various stand development stages on instream wood, sample lengths of 150 m were considered adequate. Refer to Chapter 7 for further consideration of sampling length.

Representative stream sections were only sampled if they included no major tributaries and flowed through riparian forests of uniform forest cover (i.e. similar age and species) and had no identified landslides. Riparian forest stand characteristics were based on two circular fixed-radius (0.01 ha) plots randomly placed on each streambank of the 150 m study segments. In each plot the number of trees greater than 10 cm in diameter was recorded and average tree age was based on twelve increment cores (3 per plot) collected from the dominant trees present within the sample plots. All instream wood pieces that were within or above the bankfull margins of the stream channel and were at least 10 cm in diameter and no smaller than 1 m in length were measured. The small end diameter down to 10 cm, large end diameter, and length of each wood piece situated within or above the vertical limits of channel bankfull width were recorded. The volume of each wood piece situated within or above the vertical limits of channel bankfull width was calculated as a cylinder (Hogan 1987; Robison and Beschta 1990):

$$V = L \bullet \pi \bullet \frac{\bar{d}^2}{4} \qquad (4.1)$$

where L = piece length (m) and $\bar{d}$ = mean diameter (m).

Additional characteristics such as the orientation, position, decay state and input source were also documented for each instream wood piece. The following describes the methods used in documenting the characteristics of the instream wood:

Orientation: The instream orientation of wood can affect both streamflow characteristics and channel morphology (Robison and Beschta 1990). The orientation is important in determining whether or not a wood piece has been transported downstream during high flow events. Horizontal orientation of each wood piece was grouped into two broad categories based upon the direction of streamflow: (1) perpendicular or close to perpendicular to streamflow (45-135^{o}/ 225-315^{o}), or (2) parallel or close to parallel to streamflow (45-135^{o}/ 315-45^{o}).

Position: The influence that wood has on the habitat and hydraulic characteristics of a stream channel are directly related to whether wood is suspended above bankfull height or directly present within the channel (Robison and Beschta 1990). As described by Robison and Beschta (1990), wood that is situated in the lower zone of the channel directly influences cover for fish and other aquatic organisms during periods of low streamflow. Wood situated within the upper portion of a channel below bankfull height influences streamflow hydraulics during bankfull flows resulting in the creation of pools, storage of sediment and creation of steps. Wood completely suspended above the bankfull height of a channel has direct implications for the future supply of wood to the stream channel since over time these suspended pieces will break down and become incorporated into the stream channel. As a modification from Robison and Beschta (1990), the position of each wood piece in relation to bankfull height of the channel was recorded as being in one of three positions:

- Position 1: wood that is entirely situated below bankfull height
- Position 2: wood that intersects bankfull height and is situated both below and above bankfull height
- Position 3: wood that is entirely above bankfull height

Decay State: The decay state of wood is useful for determination of the relative age and the structural integrity of the wood pieces. Similar to Hauer et al. (1999), three decay classes were used to describe the state of decay of each wood piece:

- Decay Class I: bark intact (or at least >50%), round shape with original texture and colour
- Decay Class II: trace of bark (<50% of bark remaining), twigs absent, round shape with smooth texture and darkening colour
- Decay Class III: bark absent, twigs absent, irregular shape, soft/spongy texture with many openings and dark colour.

Input Source: Determination of the source of the wood input is important in understanding the recruitment dynamics of riparian areas. Similar to May and Gresswell, (2003) and Kreutzweiser et al. (2005), the input or origin of wood source for each wood piece was documented using seven input categories: fire, chronic mortality, transport, windthrow, bank erosion, landslides or unknown. Wood from wildfire included wood pieces that had evidence of fire scars and were of a size or age that would have been present prior to the disturbance. Wood input from chronic mortality, originating from within the adjacent riparian forest, was of similar size and age to the current adjacent riparian forest stand with no attached roots or evidence of windthrow. Transported wood was located within bankfull width, had no apparent evidence of input source and showed signs of fluvial transport (e.g. fragmented pieces, abrasion, broken ends, either loose or trapped in debris jams). Wood input from windthrow also originated from the existing adjacent riparian forest stand, but showed signs of windthrow (e.g. broken/split boles, up-turned rootwad, and hummock created by upturned rootwad). Wood input from bank erosion included pieces that had roots attached to the stream bank and were undercut by streamflow and/or windthrow. Wood input from landslides included wood that was situated within landslide deposits. All remaining unidentified input sources were assigned as unknown.

Channel Characteristics: Channel characteristics within the 150 m channel segments were measured using methods similar to the approach of Kaufmann and Robison (1998). Bankfull width, bankfull depth and channel gradient were measured at eleven cross-sections spaced at 15 m intervals along the study reach. Bankfull width and height were defined by a change in vegetation (e.g. from no moss cover to moss-covered ground) and a topographic break from the channel bank to the forest floor. Width and depth measurements were measured with a metal logger's tape and channel gradient was determined with a handheld clinometer.

4.2.3 Data analysis

Data analysis included four components. The first component included an examination of several key stream geomorphic features to evaluate whether or not these features influenced instream wood quantity and volume. The key stream geomorphic features included bankfull width, basin area, channel gradient and streambed particle size ($D_{84,}$ particle diameter for which 84% of the bed surface particles are finer). The influence of these potential covariates on wood volume and number were evaluated using scatter plots, pairwise comparisons using Pearson product-moment correlations and single-factor Analysis of Variance (ANOVA).

The second component of the data analysis evaluated the temporal dynamics of wood volume and number. Single-factor ANOVA was used to evaluate wood volume and abundance in relation to four categorical stand development stages. The four stand development stages were designated by increments of fifty years (i.e. 0-50, >50-100, >100-150 and >150-200 years) and denote four stages of forest succession (i.e. regeneration, immature, mature and old forest/transition old growth). These age classes and successional stages have been used by others (Spies et al. 1988; Wells and Trofymow 1997; Clark et al. 1998) to describe the relation between terrestrial wood loading and forest stand dynamics. If significant differences were identified between categories with the ANOVA, factor level means were compared using the Tukey-Kramer multiple comparison procedure (Neter et al. 1996).

In the third component of the data analysis, two-factor ANOVA with interaction terms was used to determine whether the characteristics of wood (orientation, position or decay) varied with stand development stage. In the first case, potential differences in the volume of wood in relation to each of the orientation classes were assessed using orientation class and stand development stages as main factors. An interaction term (orientation class x stand development stage) was also included to determine whether the mean wood volume in each orientation class varied by stand development stage. The Tukey-Kramer multiple comparison procedure was then used to examine the difference in wood volume in each orientation class in relation to the stand development stages (Neter et al. 1996). The same approach was also used to assess the volume of wood in the three position categories and the four decay classes in relation to the stand development stages. Wood volume was log transformed in all three cases to ensure normality.

The fourth component included an analysis of the persistence of wood over time subsequent to the wildfire disturbance through the calculation of a depletion rate. The depletion rate was based on the change in wood storage (i.e. volume) for wood that was assumed to have either been present in the stream channels prior to the wildfire disturbance or was contributed to the stream channels due to the death of the previous, pre-disturbance, riparian forest stand as result of wildfire disturbance. The depletion rate was described as an exponential decay function (Harmon et al. 1986; Murphy and Koski 1989; Neter et al. 1996):

$$V_t = V_0^{-kt} \qquad (4.2)$$

which was linearized as follows:

$$\ln [V_t] = \ln[V_0] - kt \qquad (4.3)$$

where V_0 is the initial volume (m^3) of wood, V_t is the volume (m^3) of wood at time t (years) and k is the depletion rate coefficient ($years^{-1}$). The depletion rate was derived by regressing ln [V_t] against t and setting the slope = k and includes the reduction (i.e. decomposition, fragmentation, leaching and transport) of wood volume subsequent to the peak in wood storage associated with the wildfire disturbance. New wood that had been contributed to the streams with the regrowth of riparian forest stands following the wildfire disturbances was not included in the calculation of the depletion rate.

Diagnostic tests for homogeneity of variances and normality of distributions were checked for all linear statistical models that were used (e.g. residual plots, normal quantile plots, box-plots and Levene test) (Neter et al. 1996). Where necessary, log transformations were successfully used to correct for normality and homogeneity of variance. An alpha level of 0.05 was used to denote significant differences. The statistical software JMP developed by the SAS Institute Inc. was utilized for all statistical analyses.

4.3 Results

4.3.1 Site Summary and Geomorphic Setting

The characteristics of the twenty-six study streams that were identified for sampling are shown in Table 4.1. The study streams and their geomorphic features were found to be similar between the four riparian tree age classes (Table 4.2). The influence of key geomorphic features that included bankfull width, basin area, channel gradient and particle size (D_{84}) were not related with the total wood volume or number (Table 4.3) except that basin area was shown to be significantly related with wood number. However, because basin area was found to explain only 17% of the variation in the number of wood pieces based on a linear regression, it was not incorporated into further evaluation of the temporal dynamics of wood number. All of the study streams had boulder/cobble banks and were situated in poorly confined valleys or on open slopes and had no clearly defined flood plains and are considered to be typical of small streams in the Okanagan Highland and Thompson Plateau.

Ages of riparian forests ranged between 32 to 200 years with riparian areas dominated by either lodgepole pine or a mix of Engelmann spruce and subalpine fir with minor components of lodgepole pine (refer to Chapter 3). No riparian forest stands older than 200 years were identified for sampling, which may indicate that major disturbances have occurred relatively frequently (i.e. ~ 200 year frequency) along these small streams. Total wood volumes ranged between 0.35 $m^3/100\ m^2$ to 7.28 $m^3/100\ m^2$ with the total number of wood pieces ranging between 17 pieces/100 m to 123 pieces /100 m.

4.3.2 Wood Diameter, Length and Piece Volume

Individual piece diameters, lengths and volumes were dominated by the smaller size classes in all of the sample streams, in which case the size class distributions were positively skewed; therefore, individual median diameters, lengths and individual piece volumes were used for comparison between the four stand development stages and riparian tree age. The median diameters for all the study streams ranged between 12 cm to 22 cm and followed an inverse trend in relation to riparian tree age (Figure 4.1). The median diameter was approximately 1.5 times greater in the regeneration age (0-50 year) class as compared to the remaining three age classes (single factor ANOVA, $F_{3,22}$ = 12.11, $p < 0.01$). This pattern was also reflected in the wood volume present in three diameter classes (i.e. 10-20 cm, 21-30 cm and >30 cm) in each of the four stand development stages (Figure 4.2). In general, the proportion of wood volume in each of the diameter classes was similar between the four stand development stages except for the youngest, regeneration stage where a larger proportion of wood volume was present in the two larger diameter size classes (Figure 4.2). Median lengths within the channel bankfull width ranged between 1.5 m to 4.1 m and were poorly related with the stand development stages (single factor ANOVA, $F_{3,22}$ = 0.25, p = 0.86) (Figure 4.3). The median volume for individual pieces was consistent with diameter and followed an inverse trend in relation to riparian tree age (Figure 4.4). The individual piece volume was found to be 1.75 times greater in the regeneration stage (0-50 year) as compared to the remaining three stand development stages (single factor ANOVA, $F_{3,22}$ = 0.5.44, $p <$ 0.01, log transformation).

4.3.3 Total Wood Volume and Number

Statistically significant differences (single-factor ANOVA, $F_{3,22} = 4.46$, $p = 0.01$, log transformation) were found between the total wood volume in the four stand development stages with the total wood volume (untransformed data) being significantly lower by approximately 2.5 to 3 times in the immature (51-100 years), mature age (101 – 150 years) and old growth (151-200 years) stand development stages as compared to the regeneration stage (0-50 years) (Figure 4.2). This inverse relation with riparian tree age can also be seen in the total wood volumes from each of the individual study streams (Figure 4.5).

The number of wood pieces was more variable and not significantly related to stand development stage (single-factor ANOVA, $F_{3,22} = 0.88$, $p = 0.46$) (Figure 4.6A) and did not follow a U-shaped trend with riparian tree age (quadratic polynomial, $r^2 = 0.18$, $p = 0.09$) (Figure 4.6B).

4.3.4 Wood Characteristics (Orientation, Position, Decay and Input Source)

Orientation - In all four of the stand development stages the majority of wood was oriented perpendicular to streamflow (Figure 4.7). No statistically significant differences in wood volume were found between orientation and stand development stage (orientation x stand development stage) based on a two-factor ANOVA (Table 4.4).

Wood Position - In three out of four of the stand development stages the majority of wood volume was situated above the bankfull height (Position 3) of the channel, with the smallest wood volumes situated below bankfull height (Position 1). The remaining immature (50-100 years) stand development stage had higher wood volumes below bankfull height (Position 1) with equal wood volumes in Position 2 and 3 (Figure 4.8). However, no statistically significant differences in wood volume were found in relation to position and stand development stage (position x stand development stage) based on a two-factor ANOVA (Table 4.5).

Wood Decay State - In all four stand development stages the majority of wood volume was in an advanced state of decay (i.e. Decay Class III) with wood in Decay Class I, the earlier stages of decay, having the lowest volumes (Figure 4.9). Wood volumes in Decay Class I were significantly lower in the youngest, immature stand development stage as compared to the remaining three older stages of development after accounting for unequal variances in wood volume (log transformation) based on a two-factor ANOVA (Table 4.6). No other significant differences were observed.

Input source - The input source of instream wood was difficult to determine for the majority of wood pieces present within the sample streams and was highly variable between each of the sample streams. The input source could not be identified for 36 to 57% of the wood pieces within the stand development stages (Figure 4.10). Based only on the pieces in which the input source could be identified the majority of wood input was added to the stream channels by wildfire in the youngest age stand development stage (0-50 years). In the remaining three stand development stages no more than 2% of the wood was identified as being associated with wildfire. As expected, wood input associated with mortality (i.e. cessation, disease, insects and competition), windthrow and erosion was much higher in the latter three stand development stages as a result of single tree mortality and minor disturbances associated with development of the "new" riparian forest stand. This finding also explains the higher proportion of Decay Class I wood present within the older riparian tree age classes since chronic inputs of single trees of higher wood quality is expected in association with succession to a mature riparian forest stand.

4.3.5 Wood Depletion Rate

The trend in wood volume and number was further assessed to determine the depletion rate of the wood that was in the channel subsequent to the wildfire disturbance in the absence of the known amounts of wood that were associated with recruitment from succession and regeneration of the post-wildfire riparian forest stand. A minimum in wood volume for only those pieces that were identified as being associated with the pre-existing forest stand occurred at approximately 100 years from the time of the last major disturbance (Figures 4.11 and 4.12). This time was denoted as the time at which the majority of wood associated with the pre-disturbance riparian forest had been depleted as result of output processes associated with decomposition and transport (e.g. leaching, fragmentation and respiration). Utilizing this time and the linearized single-exponential decay model yielded depletion rate (k) coefficients of 0.05 and 0.03 for wood volume and number, respectively (Table 4.7). Therefore, based upon these depletion coefficients and the half-life, approximately 50% of the wood volume and number of pieces from the pre-existing riparian forest stand would be depleted within 45 to 55 years from the time of the last disturbance. Ninety-five percent of the volume and number of pieces would be depleted within 90 to 100 years from the time of the last disturbance.

4.4 DISCUSSION

4.4.1 Trends in Wood Storage

As highlighted in the introduction, no field studies appear to have quantified the temporal trend in wood storage in relation to time since the last major wildfire disturbance. In this study, wood volume followed a reverse J-shaped pattern in relation to the time since the last major wildfire disturbance, with the highest wood volumes being observed 30 to 50 years after wildfire with lower instream volumes observed in the latter stages of forest succession subsequent to the wildfire. These results are qualitatively consistent with the modeling results of Bragg (2000) and Benda and Sias (2003). It should be noted that this pattern is somewhat different than the U-shaped trend that is often described in the terrestrial wood literature that implies instream wood loading associated with the older riparian forests (e.g. >150 years) will be equivalent to peak loads associated with the contribution of wood from a wildfire disturbed stand (Agee and Huff 1987; Spies et al. 1988; Wells and Trofymow 1997; Feller 2003).

The observed trend in wood volume was associated with relatively large diameter pieces of wood being present in the stream channel 30-50 years after the disturbance and smaller diameter pieces present in the stream channels in association with the older riparian forests. This pattern in wood size is related to the fact that, subsequent to a major wildfire, dead dominant trees of larger diameter present within a mature riparian stand are added to the stream channel; in contrast, a stream in an older riparian forest (i.e. >100 years) will have an input of trees of smaller diameter that are being suppressed by dominant trees within the riparian forest stand. These suppressed trees of smaller diameter will contribute less to the instream volume of wood in association with older forests. This finding is supported by Harmon et al.'s (1986) synthesis, which suggests that the development of an uneven stand structure associated with growth of an older forest can lead to the input of smaller diameter pieces.

In contrast, the trend in the total number of wood pieces in relation to the riparian stand age was much more variable and was not found to be significant across the range of riparian stand development stages. The higher variability observed in the number of wood pieces is most likely related to the interplay of two main recruitment processes that are associated with the episodic delivery of wood and forest succession. As expected a higher average number of wood pieces is contributed to the streams with the episodic delivery of snags as the fire-killed riparian stand falls; however, as the riparian forest begins to regenerate, a significant number of wood pieces may be contributed to the stream associated with the stem exclusion phase of forest succession. The excluded stems could be significant in number but small in size, thus contributing a significant number of wood pieces to the stream as the riparian forest stand matures but with a relatively lower volume.

The fragmentation and decay of wood pieces is another important process that explains the relatively wide variation in wood number as compared to volume. Wood volume takes into account the actual size (diameter and length) of the pieces; therefore, as wood that was episodically delivered to the stream from the pre-disturbance forest stand decays and becomes fragmented, the actual wood volume would decrease while the number of wood pieces could remain constant or even increase as pieces of wood begin to fragment. creating several additional pieces.

Both trends in wood volume and number were evaluated in this study since it could be argued that, in smaller streams, the number of wood pieces and not the wood volume are more important in regards to the functional influence on channel morphology or aquatic habitat. Jackson and Sturm (2002) made a similar assertion where they found little relation between the size of wood and its functional role in influencing channel morphology for several smalls streams (bankfull width < 4 m) situated in the coastal region of the Pacific Northwest.

Although this study qualitatively supports the simulations of catastrophic wildfire presented by Bragg (2000) and Benda and Sias (2003), it is important to highlight that these data only provide information regarding the depletion and recruitment portion (or U-shaped trough) of the trend in wood loading. Trends associated with the input of wood associated with the toppling of fire-killed trees less than 30 years after a wildfire disturbance are not described by these data and require further study since inputs can either occur immediately or be delayed subsequent to a disturbance (Harmon et al. 1986). Also, in this study, no riparian stands older than 200 years were identified for sampling, which raises an important question in regard to the historic range of variability (Veblen

2003) of instream wood and whether or not instream wood loads in regions similar to the south-central interior of British Columbia would ever reach a long-term steady-state under “historic” conditions. This assumption has been used by other researchers in developing wood budgets for streams flowing through coastal old growth forests (e.g. Murphy and Koski 1989; Benda and Sias 2003). This assumption may not apply to the south-central interior of British Columbia, where the historic frequency of wildfire is relatively high.

In this research it was assumed that the current stand structure observed adjacent to the study streams was an artifact of major wildfire disturbances and that the stands were developing in a textbook fashion (e.g. Oliver and Larson 1996) through the phases of stand development (i.e. stand initiation, stem exclusion, understory initiation and transition to an old growth development stage) in the absence of influences from minor disturbances. However, in reality, minor disturbances that injure or kill individual trees in a forest stand as a result of abiotic or biotic disturbance factors can also play an important role in creating stand structure (Oliver and Larson 1996; Parish et al. 1999). For example, Antos and Parish (2002) studied the dynamics of a fire-initiated, old growth Engelmann spruce-subalpine fir forest in the south-central interior of British Columbia in a similar forest stand within the vicinity of this study. Based on a reconstruction of stand history using dendrochronological analysis, Antos and Parish (2002) found that although the stand was fire-initiated, the stand structure was highly influenced by a combination of minor disturbances and autogenic processes (changes in growing space caused by plant interactions). Minor disturbances associated with wind, bark beetles (e.g. mountain pine beetle, spruce bark beetle) and defoliators (e.g. spruce budworm) are common in forest stands of the southern interior of British Columbia (Parish et al. 1999; Antos and Parish 2002) and can contribute to wood loading in terrestrial and aquatic environments (Harmon et al. 1986). Much of the variability in wood loading observed in the older stand development stages in this study is likely related to minor disturbances.

The above point is important given the fact that many existing simulations (e.g. Bragg 2000, Benda and Sias 2003) of stream wood loading do not account for the many trajectories that stand structure can follow during forest development. In this study we had initially hypothesized that wood storage collected from several streams across a landscape would have a similar natural disturbance regime and would follow a similar trajectory as the simulations, but this prediction may be overly simplistic given the temporal variation observed. At the landscape level, forest stands are subjected to both major and minor disturbances with minor disturbances occurring between or in place of major disturbances (Oliver and Larson 1996). The role that minor disturbances play in generating wood in these study streams requires more research, but this study clearly shows that at the landscape level there are many additional factors related to forest stand dynamics that need to be considered, in addition to riparian tree age or stand development stage.

4.4.2 Wood Characteristics

The input sources of wood in each of the stand development stages is consistent with the forest stand dynamics of these sites, with early stages of development being dominated by inputs from fire-killed wood from the pre-existing forest stand and later stages of development having large contributions of post-fire wood from mortality and windthrow. No wood was derived from upslope sources associated with debris flows or landslides, highlighting the importance of direct wood source within one tree height (20-30 m) of the streambank. A limitation of this study is the high proportion of wood input sources that could not be identified even though this proportion was consistent with other studies (e.g. May and Gresswell 2003; Benda et al. 2002).

For the most part, wood appeared to be relatively stable based upon the fact that the majority of pieces were oriented perpendicular to the stream channel with relatively low amounts of wood observed to be transported. However, in the oldest stand development stage, higher fractions of wood were observed to have been transported. This may be an indication that wood contributed by past disturbances has become fragmented and is more easily transported through the stream.

Less wood in an earlier stage of decay within the youngest stand development stage and higher proportions of wood volume positioned below bankfull height in the immature stand development stage indicate that, during the early stages of stand development, wood that spans the channel subsequent to a wildfire begins to decay and collapse, thus becoming more integrated into the channel below bankfull height. In the later stages of forest stand development, lower volumes of "new" wood span the channels and later collapse, becoming integrated into the channel. This cyclic process may have important implications in the management of riparian areas. For example, Dahlström et al. (2005)

observed that a “substantial amount” of instream wood was derived from past wildfire disturbances that occurred before human influence in Sweden’s boreal forest. Dahlström et al. (2005) suggested that, in the absence of major wildfire disturbances that contribute large amounts of instream wood, the instream wood is likely to decrease over time. This finding raises some important research questions. Does current suppression of wildfires result in reduced wood amounts compared to historical levels? Does streamside forest harvesting in conjunction with short-term harvest rotations result in reduced instream wood? Finally, does current streamside management practices that leave narrow riparian reserves (~10 m) that may subsequently fall down contribute similar amounts of wood to streams as wildfires have in the past? Although not addressed in this research these questions are provided as a basis for future research.

4.4.3 Wood Depletion

In the literature, few studies have addressed the depletion of wood in stream environments, especially in relation to the episodic input of wood in association with wildfire. Increased understanding of the rate of depletion subsequent to disturbances such as wildfires has important implications for the design of riparian management strategies in the maintenance of long-term supply of instream wood. Coefficients for the depletion of instream wood generally range between 0.01 and 0.03 based on research conducted in coastal regions of the Pacific Northwest (Bilby 2003; Scherer 2004), with wood persisting in streams for approximately 70-100 years (Naiman et al. 2002; Hassan et al. 2005a). This is consistent with this study where a depletion rate of 0.05 was calculated.

This implies that 95% of the wood volume would be lost within 90 to 100 years subsequent to a wildfire disturbance.

Powell's (2006) research further confirms these depletion rates and residency of wood based on her dendrochronological analysis of instream wood conducted in several small streams flowing through spruce-pine forests that were dominated by stand replacing wildfires situated within the foothills of Alberta (Foothills Model Forest near Hinton, Alberta). Powell (2006) found instream wood persisted for 80 to more than 130 years, with rates of decay depending on species. For example, lodgepole pine decayed faster and had a residency of 80 years as compared to spruce species, which persisted up to 150 years. This also highlights the importance of managing riparian areas for different species such as spruce to maintain long-term supplies of wood. Similar depletion rates were also observed by Jones and Daniels (2008) in the foothills of Alberta where <12% of the instream wood persisted more than 100 years as result of decay, erosion or transport.

4.4.4 Fire Severity and Consumption of Wood

An underlying assumption of this study is that wildfires cause an increase in wood loading to riparian areas and streams; however, severe fires can also lead to consumption of wood (Pettit and Naiman 2007). Although not quantified, it is possible that some of the variability in wood loads observed in this study is associated with the consumption of wood. Quantifying the amount of wood consumed by wildfires is especially difficult for the streams flowing through the older riparian stands greater than 50 years old since evidence (e.g. charcoal, partially burnt logs or log shadows) is virtually impossible to observe. However, there was a lack of evidence to suggest that a significant amount of wood was consumed based upon general observations during surveys of the streams flowing through the youngest stand development stage (0-50 years). For example, there were few streams with partially burnt wood pieces within or above the stream channel and the density (stems per hectare) of standing or downed snags appeared to coincide well with the density of predisturbance stems (refer to Chapter 5).

In the literature, limited research has also been conducted in stream or riparian environments to quantify the actual amount of wood consumed by fires. Most of the research focused on the consumption of wood has been completed in upland forest environments. In upland forests the amount of terrestrial wood completely consumed or converted to charcoal by natural fires is quite variable (Tinker and Knight 2000). For example, Tinker and Knight (2000) found 16% of terrestrial wood was consumed or converted to charcoal subsequent to a wildfire in lodgepole pine forests in Yellowstone National Park, Wyoming. Brown et al. (1991) estimated that consumption of wood ranged from 12% to 65% in mixed northern Idaho subsequent to a prescribed fire.

The interplay of several physical factors influences the amount of wood consumed in or adjacent to a stream. These factors include fire frequency and severity, riparian characteristics (e.g. vegetation, microclimate, fuel moisture); fuel load and the geomorphic setting (Dwire and Kauffman 2003; Pettit and Naiman 2007). The frequency and severity of fires exert strong influences on the composition and structure of riparian forests and, in turn, the amount of wood (i.e. fuel load) available for recruitment into streams. Fire frequency can vary between region and forest type (Wong et al. 2003) with lower frequencies often observed in riparian areas relative to upland forests in many coastal forest regions (Dwire and Kauffman 2003). In drier forest types similar fire frequencies have been observed in riparian areas as compared to upland forests (Olson 2000; Andison and McCleary 2002). Fire severity also varies with region and forest type and is strongly influenced by riparian characteristics such as vegetation type and microclimate. The typical belief is that fire severity is lessened in riparian areas due to lower temperatures and higher relative humidity associated with dense vegetation and elevated soil moisture resulting in low wood consumption in riparian and stream environments (Pettit and Naiman 2007). This assumption does not take into account the geomorphic setting of riparian areas and streams. Low order streams tend to be more topographically continuous with upland areas and can experience similar fire regimes as upland areas; whereas, higher order streams may be more incised creating a discontinuity between the uplands and the stream (Andison and McCleary 2002; Dwire and Kauffman 2003; Pettit and Naiman 2007). Based upon the above discussion and in absence of quantitative observations one can see that it is difficult to determine the actual amount of wood consumed by fire in this study with any certainty.

4.5 CONCLUSION

In the small streams studied, wood volume followed a consistent temporal “reverse J-shaped” pattern in relation to time since the last major forest stand-replacing disturbance with evidence of a “U-shaped” pattern in wood number. The general trend was characterized by a peak in wood loading about 30-50 years following wildfire disturbances, with lower wood loadings occurring as the new riparian forest stand regenerated. In relation to time the instream wood was considered to be relatively stable based upon no evidence of landslides or debris flows that either contributed or transported wood and the high proportion of wood that was oriented perpendicular to streamflow. The position of wood changed through time with higher proportions of wood positioned below bankfull height in the immature stand development stages (50-100 years) as compared to earlier and later stages of stand development. The maintenance of instream wood loads was governed by two main recruitment processes: episodic delivery of wood 30 –50 years following the wildfire disturbances, and chronic recruitment (windthrow, disease and suppression) of wood associated with the succession of the regenerating forest stand. Based upon separation of these recruitment processes, 95% of the instream wood associated with the pre-existing forest stand appeared to be depleted 90 to 100 years after the last major wildfire disturbance.

Natural disturbances such as wildfire have been recognized as an important element in maintaining ecological functions, complexity and diversity in both forest and aquatic ecosystems. This study provides important insight into the long-term dynamics of wood and has improved our understanding of the historic range of variability of instream wood and aquatic habitat associated with wildfire disturbances. Although the linkage between ecosystem functions, aquatic organisms and instream wood are not addressed in this study, this study provides important background information that can be used to better understand the dynamic character of riparian and aquatic ecosystems in wildfire dominated forest ecosystems that are similar to the south-central interior of British Columbia. Improved understanding into the dynamics of these ecosystems is a critical element in today's forest management paradigm of natural disturbance and ecosystem-based management, which can be used to establish realistic targets for forest management planning, habitat restoration, monitoring and ecosystem sustainability.

Table 4.1. Summary of study streams used to evaluate wood loading in relation to four stand development stages.

Stream	Riparian Stand Age (years)	Gradient (%)	Mean Bankfull Width (m)	Mean Piece Diameter (cm)	Median Piece Diameter (cm)	Mean Piece Length (m)	Median Piece Length (m)	Total Volume (m^3/100 m^2)	Total Number (#/100 m)
PASAYTEN1	32	8	3.2	22.8	20.0	3.1	2.6	4.5	90
PASAYTEN2	32	7	2.9	21.4	20.0	3.0	2.6	5.8	119
SEL1	33	6	1.4	20.5	17.0	2.2	1.8	6.1	93
CANTRIB1	46	4	1.6	18.8	18.0	2.1	1.7	1.6	35
CANYON	49	6	3.4	22.5	21.5	3.3	2.5	1.4	31
HIDDEN	50	8	2.4	23.5	22.0	3.1	2.3	7.3	55
STER1	59	5	3.4	15.0	14.0	2.4	2.0	1.5	95
ELLIS	61	5	4.0	20.3	18.0	3.1	3.0	3.9	123
COLDWATERTRIB	70	5	4.5	19.8	16.0	2.8	2.5	1.6	53
COTTON1	78	10	2.4	14.2	12.0	2.8	2.6	1.0	48
PENNASK	79	2	3.5	17.8	17.0	2.9	2.4	1.2	48
SUN2	79	3	2.1	13.9	12.5	2.1	1.8	0.8	45
240CRK	84	4	3.3	15.0	13.0	2.5	2.4	1.1	71
SUN1	91	4	2.5	18.1	17.0	2.9	2.5	1.8	50
CORTRIB	115	8	1.4	15.1	13.5	2.1	1.6	1.6	57
UWKTRIB1	115	8	1.1	18.1	16.0	1.7	1.5	3.7	72
BEAKUPPER	116	6	2.6	15.4	15.5	2.0	1.7	0.3	24
VENTURI	118	14	3.5	19.0	15.0	4.3	4.1	2.2	47
MUNCRK2	120	6	3.4	13.7	12.0	2.7	2.3	0.8	61
NICTRIB1	123	2	1.6	19.5	15.5	2.0	1.7	0.8	17
DOME1	157	1	2.1	17.6	15.5	2.1	2.0	1.2	42
DARLEY	165	7	3.0	16.8	15.0	2.5	2.3	2.5	100
LOWERCORP	186	4	2.9	15.7	14.0	2.7	2.3	2.3	97
MUNCRK1	186	7	2.0	14.9	14.0	2.0	1.9	1.0	50
DOME2	194	8	2.8	16.6	14.8	2.9	2.6	1.4	49
REED1	200	5	2.4	17.0	14.5	2.2	2.1	1.3	50

Table 4.2. Comparison of study streams in relation to stand development stages (means and standard deviations in each development stage are provided with minimum and maximum values provided in brackets). F statistics and associated p-values for one-way ANOVAs are shown.

	Stand Development Stage (years)				$F_{3,22}$	p value
	0 - 50	**51 - 100**	**101 - 150**	**151 - 200**		
Number of Sample Streams	6	8	6	6		
Bankfull Width (m)	2.5 ± 0.8 (1.4 – 3.4)	3.2 ± 0.8 (2.1 – 4.5)	2.3 ± 1.0 (1.1 – 3.5)	2.5 ± 0.4 (2 – 3)	1.82	0.17
Gradient (%)	6 ± 1.5 (4 – 8)	5 ± 3 (2 – 10)	7 ± 4 (2 – 14)	5 ± 2 (1 – 8)	1.19	0.34
Drainage Area (ha)	460 ± 288 (175 – 837)	792 ± 532 (179 – 1582)	446 ± 338 (81 – 786)	517 ± 249 (231 – 942)	1.11	0.36
Elevation (m)	1510 ± 114 (1400 – 1720)	1400 ± 174 (1100 – 1670)	1482 ± 187 (1220 – 1700)	1538 ± 62 (1460-1600)	1.19	0.34
D84 (mm)	144 ± 136 (16 – 380)	96 ± 77 (14 – 220)	163 ± 128 (30 – 350)	217 ± 168 (24 – 500)	1.07	0.38
Current Stand Age (years)	40 ± 9 (32 – 50)	75 ± 11 (59 - 91)	118 ± 3 (115 – 123)	181 ± 17 (157 – 200)	184.59	**<0.01**

Table 4.3. Pairwise correlations between total wood volume and number in relation to key geomorphic features.

Pairwise Correlations	Pearson r	p-value
Total Wood Volume (m^3 / 100 m^2) and Geomorphic Variables		
Bankfull Width	-0.10	0.63
Basin Area	-0.02	0.93
Channel Gradient	0.28	0.17
Particle Size	-0.24	0.23
Elevation	0.16	0.43
Total Wood Number (# / 100 m) and Geomorphic Variables		
Bankfull Width	0.25	0.21
Basin Area	0.41	0.03
Channel Gradient	0.11	0.60
Particle Size	-0.32	0.11
Elevation	0.05	0.82

Table 4.4. Summary of two factor analysis of variance for total volume (log transformation) after accounting for the interaction between the stand development stages and the two orientation classes (Perpendicular or Parallel).

	DF	F ratio	p value
Whole Model	7	3.35	0.006
Stand Development Stages	3	5.36	0.003
Orientation Class	1	6.74	0.012
Stand Development Stages x Orientation Class	3	0.189	0.904

Table 4.5. Summary of two factor analysis of variance for total volume (log transformation) after accounting for the interaction between the stand development stages and the three position categories.

	DF	F ratio	p value
Whole Model	11	2.86	0.004
Stand Development Stages	3	6.96	<0.001
Position	2	2.45	0.094
Stand Development Stages x Position	6	1.09	0.377

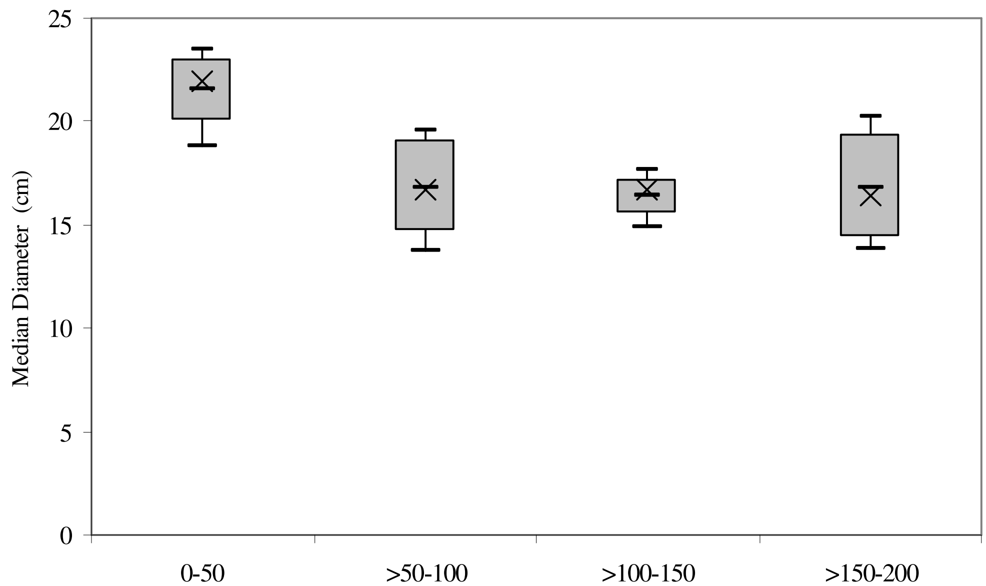
Table 4.6. Summary of two factor analysis of variance for total volume (log transformation) after accounting for the interaction between the stand development stages and decay classes.

	DF	F ratio	p value
Whole Model	11	11.25	<0.001
Stand Development Stages	3	1.38	0.256
Decay Class	2	40.91	<0.001
Stand Development Stages x Decay Class	6	6.02	<0.001

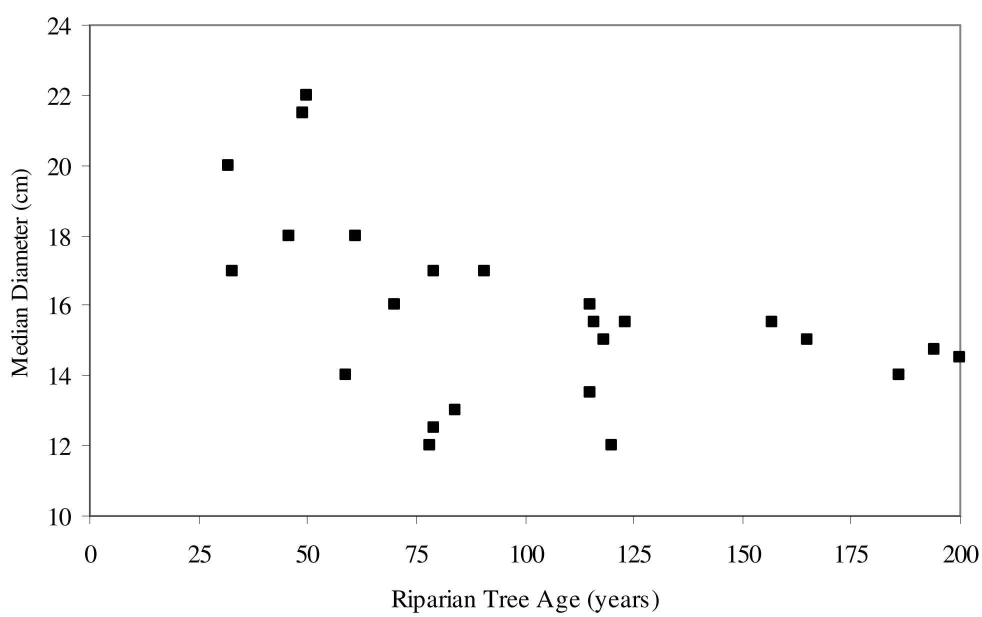
Table 4.7. Depletion coefficients for wood volume and number based only on the wood that was assumed to be associated with the pre-existing riparian forest stand prior to the last major wildfire disturbance.

	Depletion Coefficient (S.E.)	n	Intercept (S.E.)*	p value	Adjusted-r^2
Wood Volume ($m^3/100m^2$)	0.05 (0.007)	14	6.0 (1.3)	<0.001	0.75
Wood Number (# / 100 m)	0.03 (0.006)	14	39 (1.3)	0.007	0.60

* intercept value represents average volume at 31 years.



(A)



(B)

Figure 4.1. Median wood diameters in relation to stand development stage and riparian tree age: (A) Box plot showing the median diameters in each of the stand development stages. In the box plot, means are represented as crosses, medians are represented as a line, bars represent upper and lower quartiles and whiskers denote the range; (B) median diameter vs. riparian tree age.

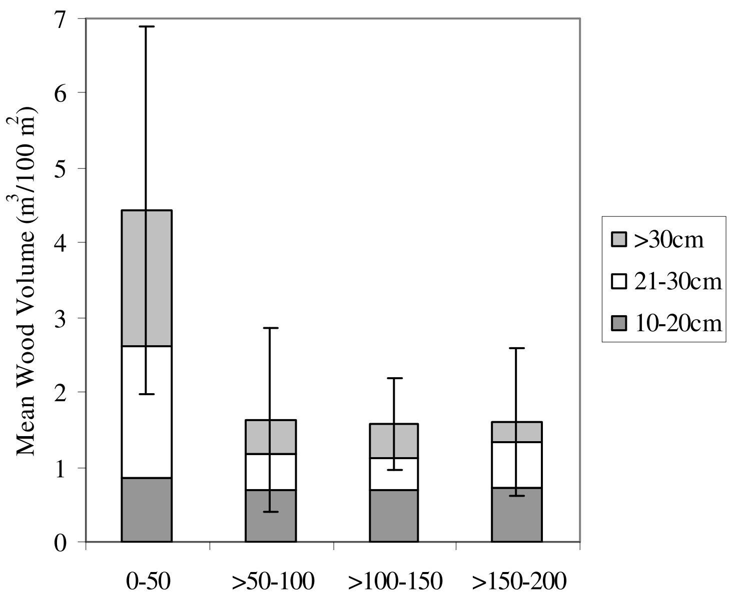
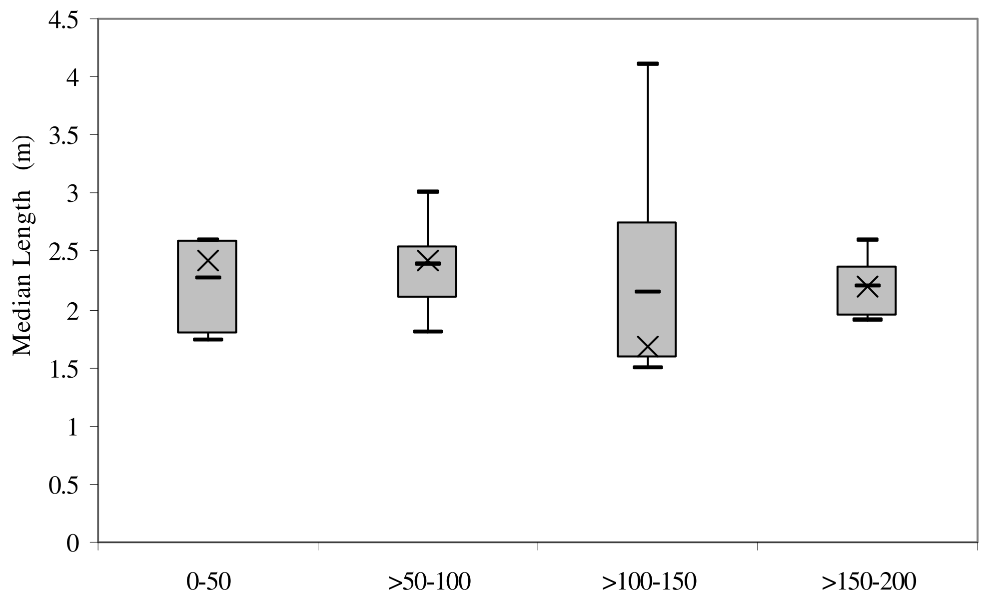
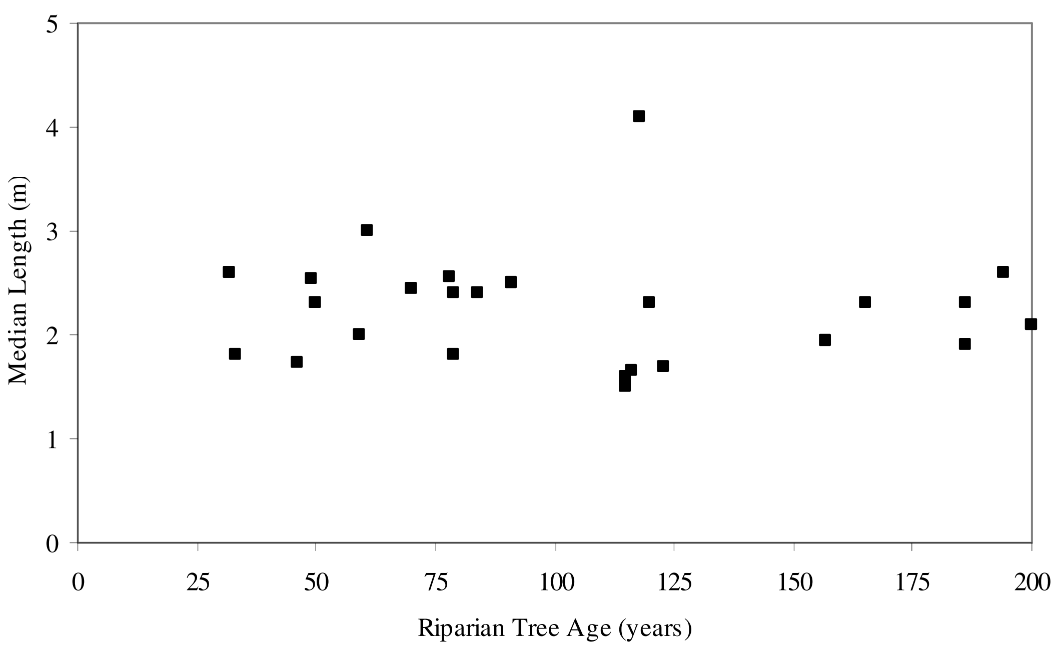


Figure 4.2. Mean wood volume in three diameter classes in relation to stand development stage. Standard deviations denoted by error bars.

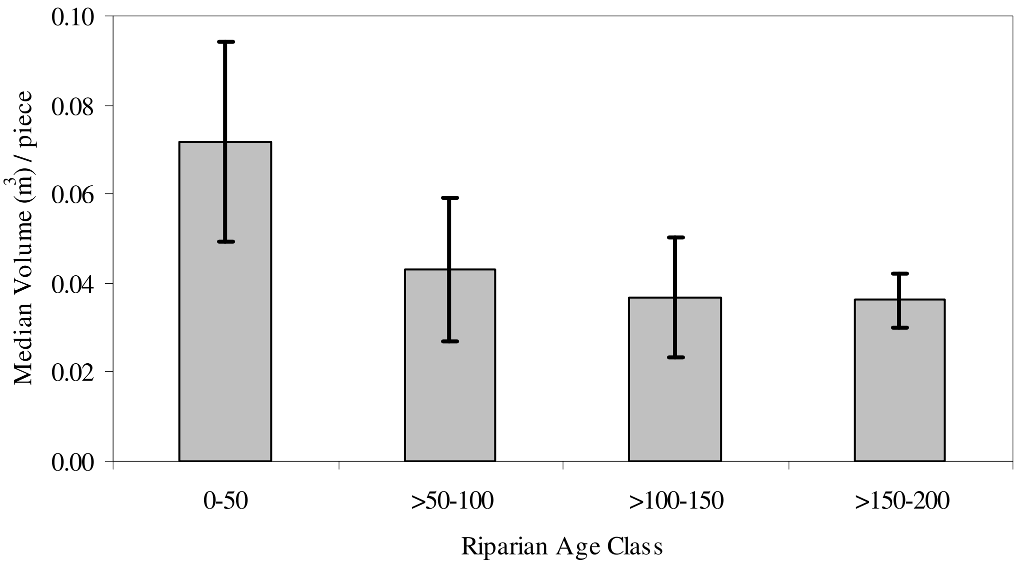


(A)

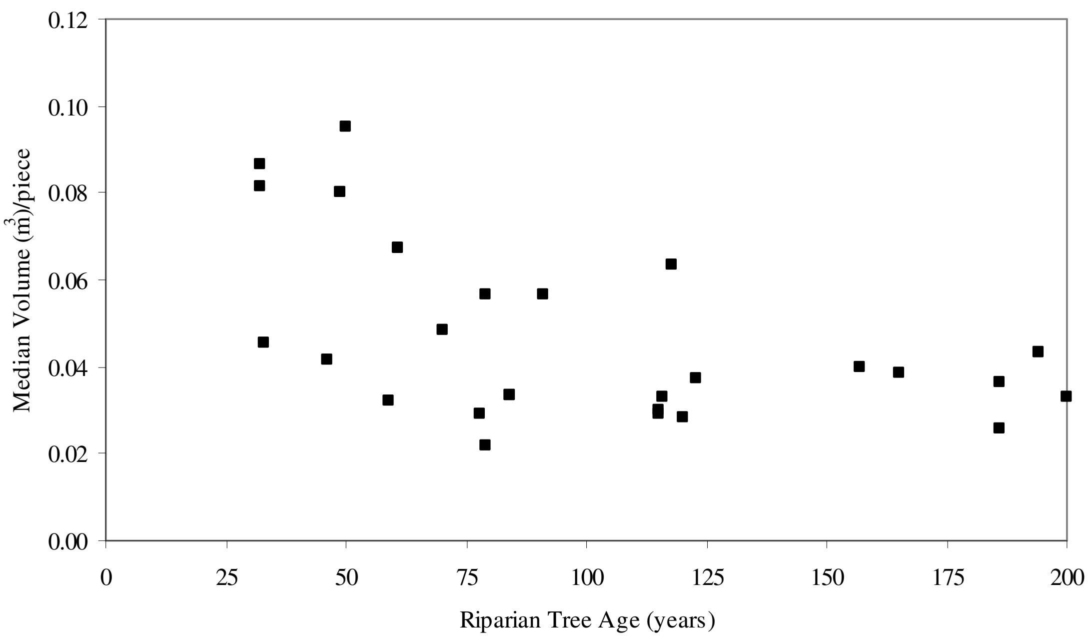


(B)

Figure 4.3. Median wood length within bankfull width in relation to the four stand development stages and riparian tree age: (A) Box plot showing the median lengths in each of the stand development stages. In the box plot, means are represented as crosses, medians are represented as a line, bars represent upper and lower quartiles and whiskers denote the range; (B) median length vs. riparian tree age.



(A)



(B)

Figure 4.4. Wood piece volume in relation to stand development stage and riparian tree age: (A) mean of median volume (m^3) per piece vs. stand development stage (B) volume (m^3) per piece vs. riparian tree age. Standard deviations denoted by error bars.

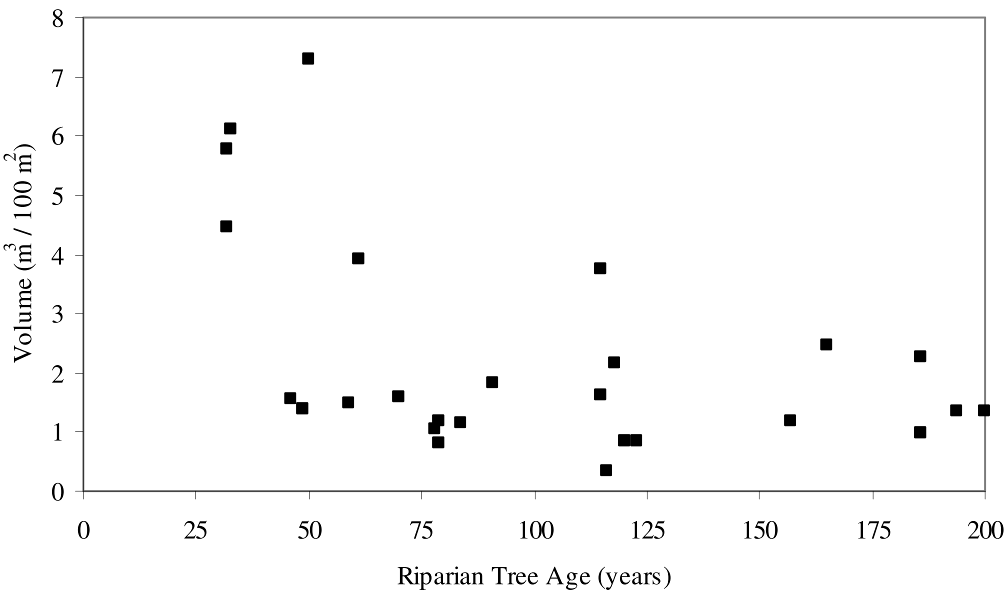
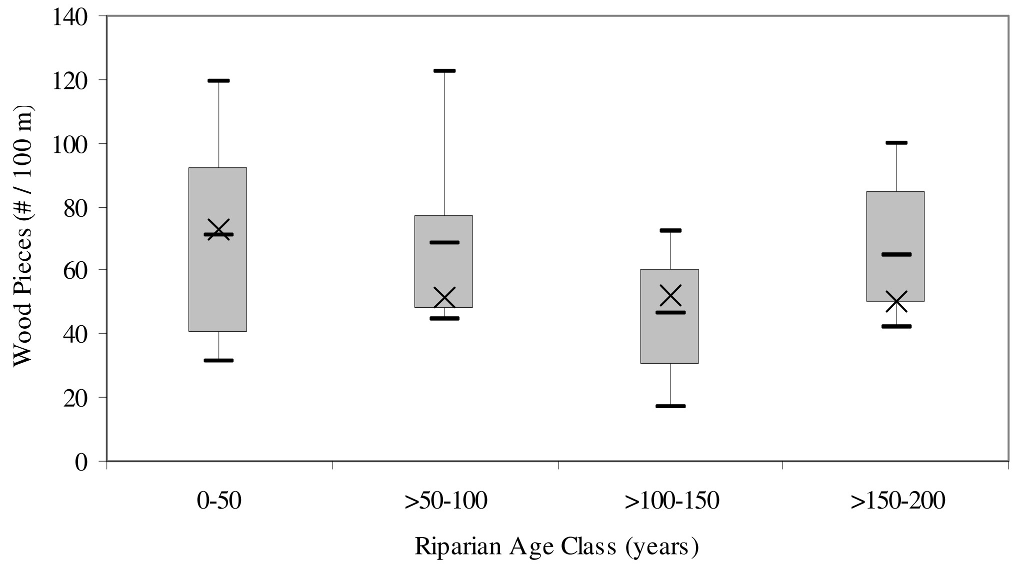
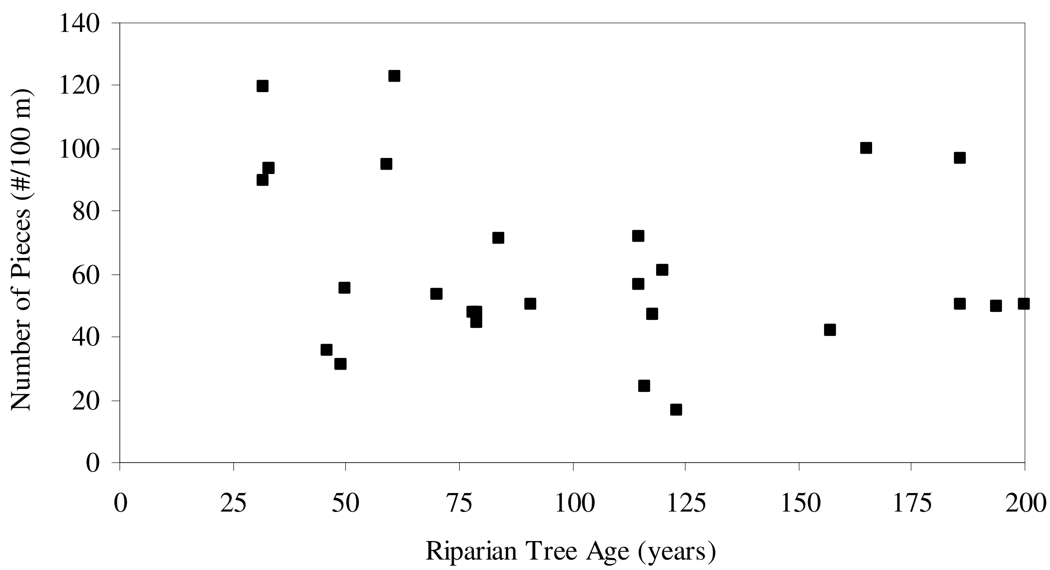


Figure 4.5. Total wood volume in relation to riparian tree age.



(A)



(B)

Figure 4.6. Total wood number in relation to the four stand development stages: (A) Box plot showing the number of pieces in each of the stand development stages. In the box plot, means are represented as crosses, medians are represented as a line, bars represent upper and lower quartiles and whiskers denote the range; (B) Number of pieces versus riparian tree age.

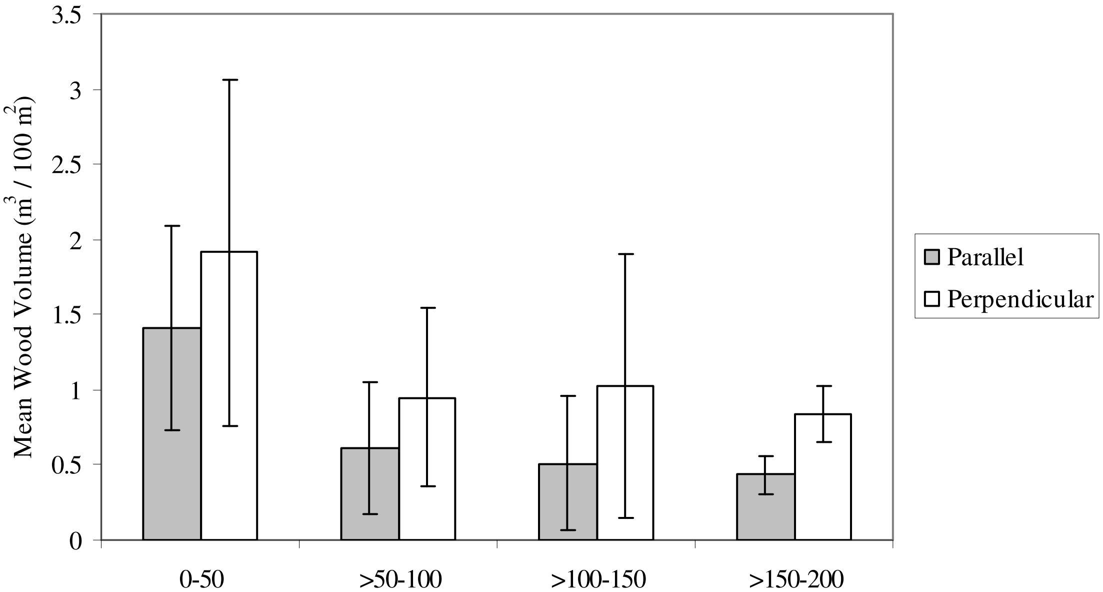


Figure 4.7. Mean wood volume by orientation class (parallel or perpendicular) in each of the four stand development stages. Standard deviations indicated with error bars.

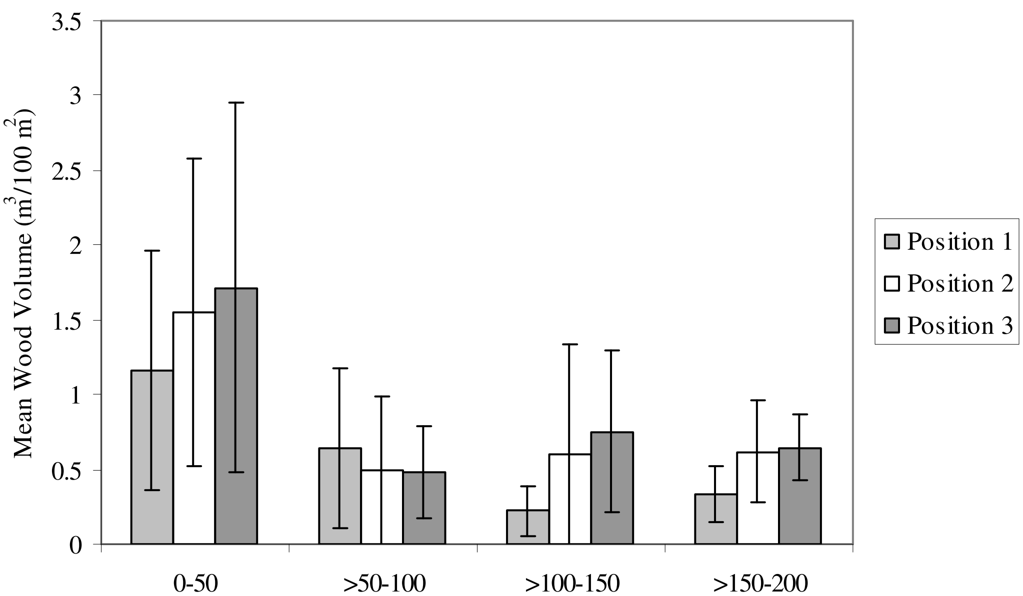


Figure 4.8. Position of wood in relation to the four stand development stages. Standard deviations denoted by error bars. Three positions are: (1) wood that is entirely situated below bankfull height; (2) wood that intersects bankfull height and is situated both below and above bankfull height; and, (3) wood that is entirely above bankfull height.

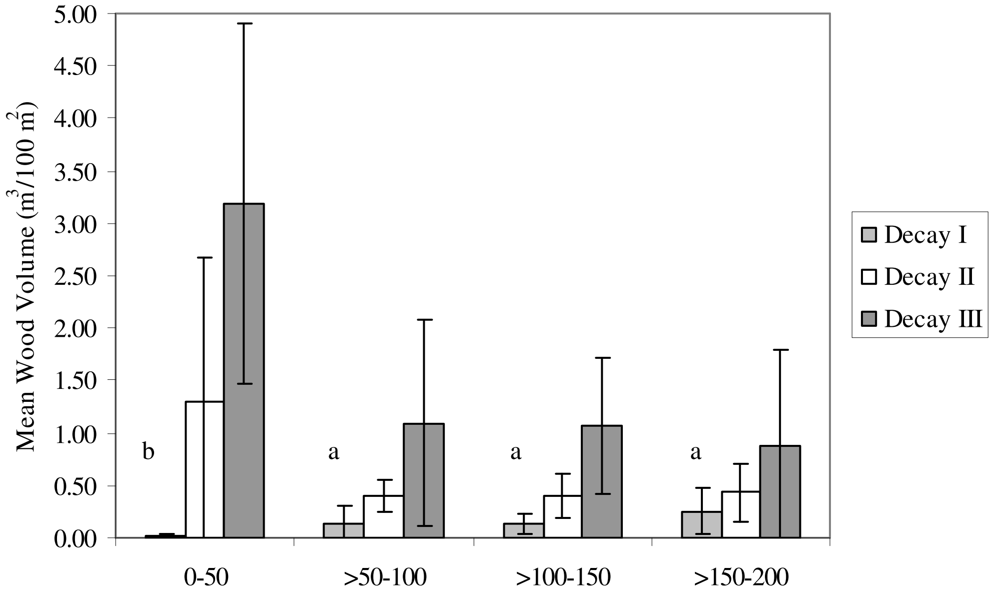


Figure 4.9. Mean wood volume ($m^3/100\ m^2$) by Decay Class in the four stand development stages. Error bars indicate one standard deviation. Significant difference in wood volume in each Decay Class denoted with letters (i.e. a > b).

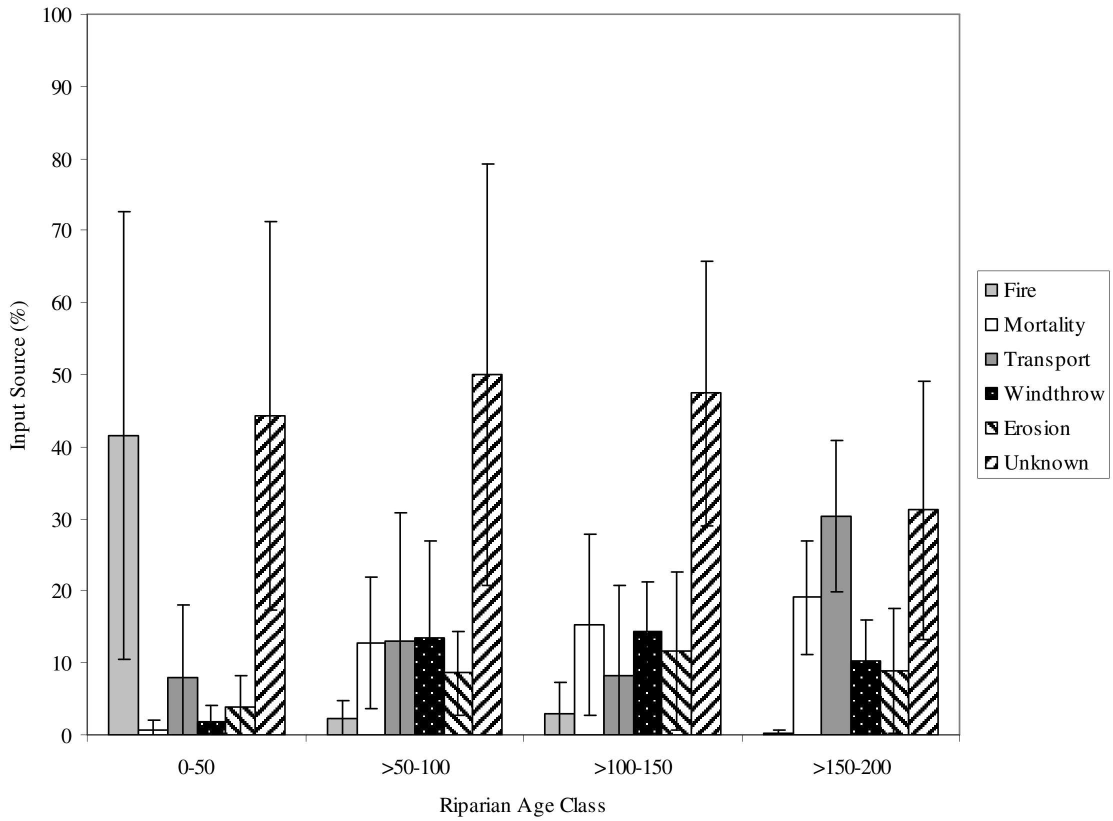


Figure 4.10. Input source (percent of number) by stand development stage. Standard deviations denoted by error bars. (Note: no wood from landslides was identified).

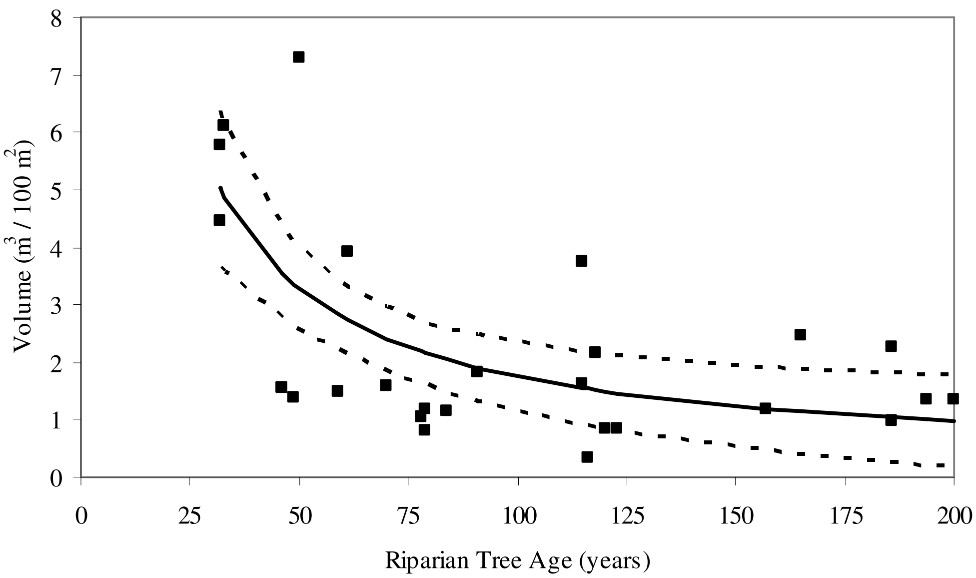


Figure 4.11. Wood volume in relation to riparian tree age with exclusion of wood volume from known input sources associated with the regeneration of the post-fire riparian forest stand. Exponential decay function denoted by solid line with 95% confidence intervals denoted by dashed lines.

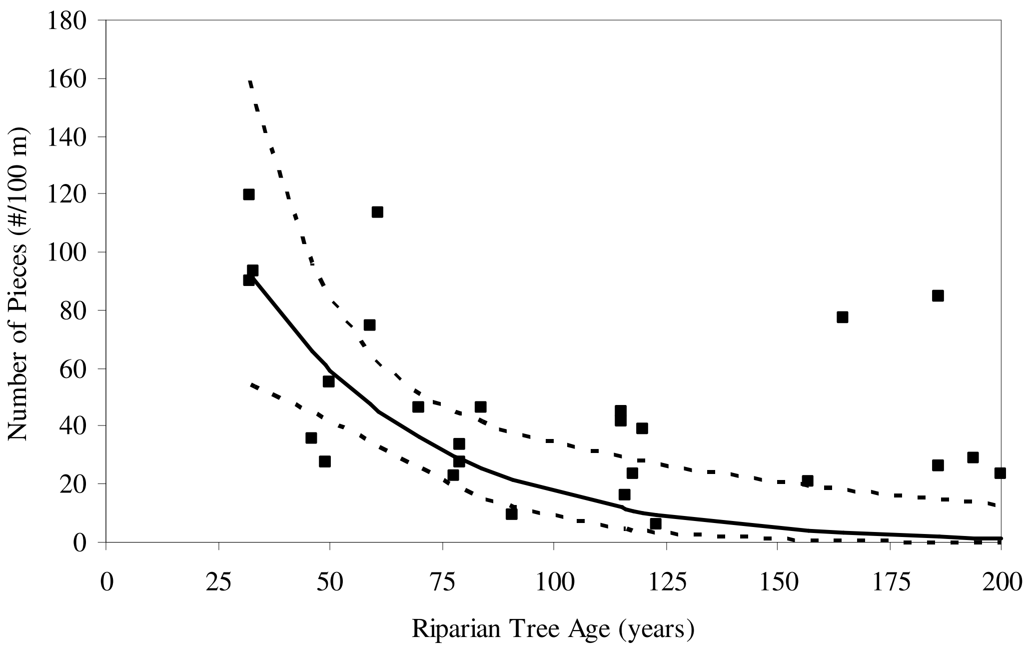


Figure 4.12. Total number of wood pieces in relation to riparian tree age with exclusion of wood pieces from known input sources associated with the regeneration of the post-fire riparian forest stand. Exponential decay function denoted by solid line with 95% confidence intervals denoted by dashed lines.

CHAPTER 5

COMPARISON OF WILDFIRE DISTURBANCES AND STREAMSIDE CLEARCUT HARVESTING ON INSTREAM WOOD

5.1 INTRODUCTION

Few field studies have compared wood supply and storage in small streams affected by stand-replacing wildfire disturbances and clearcut harvesting. Computer simulations suggest that instream wood supply and storage following wildfire tend to be high, with the majority of wood entering the stream channel approximately 25-50 years after the disturbance (Bragg 2000, Benda and Sias 2003). Wood loads then decline over time as the regenerating forest contributes little wood input. As the forest matures, an increased delivery of wood occurs from self-thinning-based tree mortality and small-scale disturbances (e.g. windthrow, disease, and insects).

Streamside clearcutting affects instream wood dynamics differently, with an initial decline in instream wood supply and storage. However, field research from the coastal Pacific Northwest has found both increases and decreases in the number and volume of wood pieces after logging. These conflicting findings may be attributable to differences in management guidelines and practices (e.g. slash removal versus non-removal), size distribution of wood, and the time since the occurrence of logging (Hassan et al. 2005a).

The objective of this chapter was to compare the amounts (i.e. volume and number) and characteristics (orientation, position, decay state and input) of instream wood between several small (<3rd order) streams flowing through old riparian forests and disturbed riparian forests affected by streamside clearcutting or stand-replacing wildfires. This information is critical to establishing realistic reference loadings or targets for forest management planning, habitat restoration, monitoring and ecosystem sustainability.

This chapter focused on the following primary hypotheses:

1. Number of pieces and volume of wood are greatest in small streams following stand-replacing forest fires within the last fifty years as compared to streams in old-growth or unharvested forests (i.e. > 120 years).
2. Small streams in clearcut harvested forests will have lower volume and fewer pieces of wood as compared to streams in old-growth or unharvested forests.
3. Wood characteristics (i.e. size, orientation, position, decay and input) will be altered in streams disturbed by streamside clearcut harvesting and wildfire as compared to old-growth or unharvested forests. Hypothesized changes include:
    a. A decrease in wood piece size in relation to streamside clearcut harvesting;
    b. An increase in wood volume oriented parallel to streamflow following streamside clearcut harvesting due to increased mobility of wood associated with increased channel instability and streamflows;
    c. A decrease in wood volume spanning stream channels following streamside clearcut harvesting; and,
    d. An increase in wood volume in an advanced state of decay following streamside clearcut harvesting.

5.2 METHODS

5.2.1 Sample Streams and Study Design

A multiple-stage sampling design was used to randomly select the study streams from three general categories of streams (clearcut harvested, wildfire-disturbed and old-growth). A total of 26 small (2^{nd} or 3^{rd} order on 1:30,000 scale forest cover maps) stream reaches with bankfull widths less than 4 m were selected within the Okanagan Highland and Thompson Plateau study area (refer to Chapter 3). As described in Chapter 4, all potential sample streams were first identified and classified by stream order on 1:30,000 scale BC Ministry of Forests forest cover maps and were only chosen if specific criteria was met. Only stream channels with similar geomorphic settings were studied to reduce geomorphic sources of variation. The study employed a retrospective approach because pre-disturbance data were not available for the study sites.

Sample streams were then grouped into four disturbance categories: (1) Old Forests, (2) Wildfires, (3) clearcut in the 1990s (Harvest 90); and (4) old harvesting from the 1960s and 1970s (Harvest 70). The clearcut sites were grouped into two categories to account for the influence of time since harvest on instream wood. Although inclusion of an additional clearcut category, harvested 50 to 75 years ago, would have been preferred, this was not possible given the relatively short history of logging in the area. All clearcut sites were logged by conventional harvesting systems (i.e. hand- or machine-falling and ground skidding). The Old Forest category was defined as forests that had not experienced any major disturbances for at least 120 years, while the Wildfire category included only those forests that had burned in the last twenty to fifty years with fires that were severe enough to kill the standing trees. The number of study sites in the Wildfire and Harvest 70 categories was limited since only streams that met the geomorphic criteria were included. Study streams within wildfires were particularly difficult to find since few large wildfires had occurred within the study area over the last twenty to fifty years.

The sample streams were grouped into the four disturbance categories based on two circular fixed-radius (0.01 ha) plots randomly placed within 10 m of the stream channel on each side of the 150 m study streams. These plots sampled approximately 5% of the riparian area within a distance of one tree height from the stream edge. Live trees and snags with diameters greater than 10 cm diameter at breast height (1.3 m from the ground) were measured. Pre-disturbance stand characteristics for the clearcut logged riparian areas were based on the diameter, age and species (i.e. tree bark) of remaining tree stumps and historic forest cover information. Pre-wildfire stand characteristics were based upon the diameter, age and species as determined from snags and historic BC Ministry of Forests forest cover maps. All sampling occurred from August to October in 2003 and 2004 during the summer/fall low flow period.

In the 1970s and 1980s, removal of logging debris along with pre-existing instream wood was often mandated in the Pacific Northwest subsequent to logging to ensure passage of anadromous fish (Bilby 1984). However, no such activities or requirements are known to have existed in this study area, given local knowledge and the lack of visual evidence of stream cleaning (e.g. bucked logs in or along the channel).

5.2.2 Field Methods

Wood volume, number and characteristics were determined using the same methodology as described in Chapter 4 based on the standardized approach developed by the United States Environmental Protection Agency's Environmental Monitoring and Assessment Program (Kaufmann and Robison 1998).

In addition to the field methodology followed in Chapter 4 each wood piece was also identified as being either geomorphically functional or non-functional. Similar to Jackson and Sturm (2002), functional wood was defined as any piece that created pools, stored sediment, maintained bank stability (i.e. situated along channel bank deflecting stream flow away from the bank) or trapped small wood pieces (<10 cm in diameter). Non-functional wood was any piece that did not provide any of the geomorphic functions identified above.

5.2.3 Data analysis

Wood volume, number of pieces, the number of wood pieces less than 10 m in length and other characteristics were compared between the four disturbance categories using single-factor analysis of variance (ANOVA). Homogeneity of variances and normality of distributions were tested and where necessary, cube root or log transformations were used successfully to correct problems with normality and homogeneity of variance. Significant differences between factor level means were compared using the Tukey-Kramer multiple comparison procedure (Neter et al. 1996).

The Kruskal-Wallis rank sum test was used to compare the median diameter and length of the wood pieces between each of the disturbance categories since these size distributions were positively skewed. Median diameters and lengths were used instead of the means to better represent central tendencies for each disturbance category (Gomi et al. 2001). The Kruskal-Wallis rank sum test was also used to compare current stand characteristics between the four disturbance categories since transformations did not correct for unequal variances.

To investigate whether there was an increase of wood volume in an advanced state of decay following streamside clearcut harvesting, a two-factor ANOVA was used with disturbance category and decay class used as the two factors. An interaction term (disturbance category x decay class) was also included to determine whether the mean volume in each decay class varied by disturbance category. To ensure normality, a cube root transformation was successfully used to produce a normal distribution. The Tukey-Kramer multiple comparison procedure was then used to identify which treatments differed from the others (Neter et al. 1996).

Two-factor ANOVA with interaction terms was also used to compare wood volume between the following sets of factors: the two orientation classes and the four disturbance categories, and the three wood position categories and the four disturbance categories. Wood volume was log transformed in both cases to ensure normality. Tukey-Kramer multiple comparisons were then used to compare wood volumes. A significance level of

0.05 was used for all statistical tests. Statistical analyses were conducted using JMP (SAS Institute).

5.3 Results

5.3.1 Comparison of Sample Stream and Riparian Stand Characteristics

The 26 sample streams had similar channel bankfull widths, channel gradients and drainage areas between the four disturbance categories; however, the average bankfull depth was significantly shallower in the Harvest 90 category than in the remaining three categories (Table 5.1). This was not considered to be a major geomorphic difference since all the channel depths were within 10 cm of each other. Pre-disturbance riparian forest stand characteristics were similar between the clearcut and wildfire disturbance categories. The average stem density, basal area and snag density of the current riparian stands were significantly different between the four disturbance categories with few to no stems greater than 10 cm in diameter measured in the Harvest 70 and Harvest 90 disturbance categories. Current riparian stand conditions in the Wildfire disturbance category were intermediate to the two harvest categories and the Old Forest category. In the Wildfire category, 40% of the snags remained standing in two out of six of the study sites with 0 to 7% of the snags still standing in the remaining four study sites. No standing snags were observed in the Harvest 70 or 90 categories. All the standing snags in the Old Forest category came from the current riparian stands (e.g. absence of fire scars), and none were “veteran” snags that existed prior to historic fires.

5.3.2 Wood Diameter, Length, Number and Volume

Both the individual piece diameters and lengths were dominated by the smaller size classes. The median piece diameters for all the study streams ranged from 12 cm to 22 cm and median lengths ranged from 1.7 m to 2.7 m (Table 5.2). Median diameters were significantly larger (Kruskal-Wallis rank sum test $X^2 = 13.52$, $p \leq 0.01$) in the Wildfire disturbance category as compared to the other three categories (Old Forest, Harvest 90, Harvest 70). No significant differences in the median lengths of wood within the bankfull width of the stream channels were found between the four disturbance categories (Kruskal-Wallis rank sum test $X^2 = 0.58$, $p = 0.90$). However, when total piece lengths were examined, the average number of pieces longer than 10 m was significantly greater in the Wildfire category (33 pieces / 100 m) than in the Harvest 90 (18 pieces / 100 m), Old Forest (15 pieces / 100 m) and Harvest 70 (10 pieces / 100 m) categories (ANOVA $F_{3,22} = 7.17$, $p = 0.002$).

The total number of wood pieces was highly variable (17 to 119 pieces per 100 m, mean = 69, SD = 27), and the number of functional wood pieces ranged from 11 to 104 pieces per 100 m (Table 5.2). On average, 62% (range, 16 to 91%) of the total number of wood pieces was considered to be functional. No statistically significant differences in the total number of wood pieces were found between the four disturbance categories (Figure 5.1; Table 5.3). The mean number of functional wood pieces for the Harvest 90 and the Harvest 70 disturbance categories (Figure 5.2; Table 5.3) were approximately two and a half times higher than in the Old Forest category.

Across all of the study streams, the total wood volume ranged between 0.8 and 7.3 m^3 per 100 m^2 of bankfull channel. Total functional wood volume ranged between 0.4 m^3/100 m^2 and 5.3 m^3/100 m^2. Total wood volume was found to be significantly greater in the Wildfire category as compared to the Old Forest category (Figure 5.3; Table 5.3) with no significant differences between the Harvest 90 and Harvest 70 categories and either the Old Forest or Wildfire categories. However, average total volume in the Wildfire category was approximately three times greater than in the Old Forest category. Based on untransformed values, average functional wood volumes were significantly (3 to 4 times) higher in the Wildfire, Harvest 90 and Harvest 70 disturbance categories when compared to the Old Forest category (Figure 5.4; Table 5.3).

Although the relation was not statistically significant ($F_{1,9}$ = 1.83, p = 0.209, r^2 adj. = 0.08), total wood volume appeared to decrease linearly with time since harvest when only the harvested sites were considered (Figure 5.5). This analysis included the removal of one study stream that was considered an outlier (TERRACE1) since this stream was observed to have an unusually large addition of wood associated with a log bridge that had been placed in the channel and was most likely used for skidding. In addition, the total number of pieces was not significantly related with the time since harvest ($F_{1,9}$ = 0.291, p = 0.600, r^2 adj. = 0.00).

5.3.3 Wood Characteristics

Orientation - In all four disturbance categories the majority (59% to 65%) of all wood was oriented perpendicular (or close to perpendicular) to streamflow (Figure 5.6).

Functional wood was similarly oriented, with 57% to 65% of the functional wood pieces perpendicular to streamflow. No statistically significant differences in wood volume were found between orientation and stand development stage based on a two-factor ANOVA (Figure 5.6, Table 5.4).

Wood Position - The wood volume in each of the three channel positions and disturbance categories is shown in Figure 5.7. The most apparent difference between the disturbance categories can be seen in the volume of wood situated in Position 1 and Position 3. Significantly greater wood volumes were observed below bankfull height (Position 1) in the Harvest 90, Harvest 70 and Wildfire categories as compared to the Old Forest Category (Table 5.5). The wood volumes were significantly higher above bankfull height (Position 3) in the Wildfire category compared to the Harvest 70 and Old Forest categories. Wood volumes in Position 2 were significantly greater in the Harvest 70, Harvest 90 and Wildfire categories compared to the Old Forest category (Table 5.5).

Wood Decay State - In all of the disturbance categories, most wood was in an advanced state of decay (i.e. Decay Class III). Wood in Decay Class I, the earlier stages of decay, had the lowest volumes (Figure 5.8). Wood volume in the Decay Class 1 was found to be significantly lower in the Harvest 70 category as compared to the Old Forest category after accounting for unequal variances in wood volume (cube root transformation) based on a two-factor ANOVA (Figure 5.8, Table 5.6). Wood volumes in an intermediate stage of decay (Decay Class II) were also significantly lower in the Harvest 70 category as compared to the Wildfire category. Wood volumes in the latter stage of decay (Decay

Class III) were lower in the Old Forest category as compared to the Wildfire Category. No other paired comparisons specific to each of the individual decay classes and the disturbance categories were found to be significant. However, based upon an interaction plot between decay class and disturbance category, there is weak evidence that wood volumes in the latter stages of decay are lower in the Old Forest category as compared to the other three disturbance categories (Figure 5.9).

Input Source - The input source of instream wood was difficult to determine for the majority of wood pieces present within the sample streams and was highly variable between each of the disturbance categories. The input source could not be identified for 24 to 68% of the wood volume within the four disturbance categories (Figure 5.10). Based only on the wood volume for pieces in which the input mechanism could be identified, the main input mechanisms in the two harvest categories were related to forest harvesting and either the mortality, windthrow or erosion of residual trees that were left subsequent to logging. In the Old Forest category the majority of wood input was associated with mortality (i.e. cessation, disease, insects and competition), windthrow and erosion. As expected, fire accounted for the highest proportion of wood input in the Wildfire disturbance category.

5.4 DISCUSSION

5.4.1 Disturbance Effects on Instream Wood Loading

As anticipated, higher total and functional wood volumes were recorded in the Wildfire category than in the Old Forest category (Table 5.3). However, both had similar numbers of pieces of total and functional wood. Piece size may help account for this inconsistency. The diameter of wood and the number of long pieces (length > 10 m) was greater in the Wildfire category than in the Old Forest category; hence, the higher volumes are a logical consequence of larger piece sizes. The larger diameters result from the catastrophic recruitment of large, old growth trees.

Another possible explanation for the difference between number of pieces and piece volume between the Old Forest and Wildfire categories may lie in differences in processes (i.e. forest succession versus an episodic input from fire). For example, Harmon et al. (1986) and Franklin et al. (2002) stated that the development of an uneven-aged stand structure associated with growth of an older forest can lead to the input of smaller diameter pieces as result of stem exclusion. Therefore, although the wood volume is lower in the Old Forest category, the number of wood pieces may be similar between the two disturbance categories. Chronic processes such as windthrow and bank erosion could also contribute smaller sized pieces to a stream during forest development. Thus, when evaluating differences between disturbances, both wood volume and number should be measured, since these two parameters may not be directly related. This point is especially important in small streams where relatively small wood pieces (diameters between 10 cm to 40 cm) can have a major influence on channel morphology (Jackson and Sturm 2002).

A common perception is that clearcut harvesting results in reduced instream wood volumes and numbers of pieces; however, these results do not support this perception.

There are two main explanations, the first and most likely for these sites is that non-merchantable trees may have been left adjacent to the streams and live trees that were leaning over the stream channel may have been cut and left across the stream channel to avoid potential skidding damage during logging. Along with contributions from logging slash, these trees may become incorporated into the stream channel and thus maintain wood supply (at least temporarily) subsequent to forest harvesting. This result is consistent with other studies where an increase in wood was attributed to contributions from logging slash recruitment (Swanson et al. 1984; Gomi et al. 2001). A second explanation relates to the transport and decay of wood through these stream systems. Some studies have shown a decrease in wood following streamside clearcut harvesting due to bank destabilization, channel widening and landslides and debris flows following logging that scour large amounts of wood (Beschta 1984, Hogan 1986, Gomi et al. 2001). However, the study streams in this study, which are typical for small streams situated within the south-central and central interior of B.C. (refer to Chatwin et al. 2001; Church and Ryder 2001), were characterized by stable channel banks, moderate hillslope and channel gradients with no evidence of mass wasting events. These factors, coupled with the large proportion of wood oriented perpendicular to the channel, suggest that wood transport was low. As discussed in Chapter 4, in absence of mass wasting events wood may persist up to 100 years in small streams that have limited capacity to transport wood (Hassan et al. 2005a).

If transport is low, as appears to be the case, instream wood loss would then be largely related to decomposition. Decomposition of wood in stream environments is complex and involves many biological and physical processes that include biotic consumption, leaching, decay and physical fragmentation (Harmon et al. 1986). Decomposition rates for instream wood depend on a range of environmental factors including climate, tree species, position in stream channel (e.g. suspended, fully submerged or buried in channel) and moisture levels (Harmon et al. 1986, Naiman et al. 2002). Unfortunately, only limited research on decomposition rates in stream environments is available. Studies in the coastal regions of the Pacific Northwest suggest decomposition rates generally range between 0.01 and 0.03 yr^{-1} (Bilby 2003, Scherer 2004), with wood persisting in stream channels for approximately 70-100 years (Naiman et al. 2002).

The functional wood volume and number of pieces were higher in the two harvest categories as compared to the Old Forest category. In the harvest categories, there was a high proportion of wood in the most advanced state of decay (Decay Class III) which has led to the collapse and breakdown of wood pieces into the lower portions of the stream channel, thereby contributing higher volumes and numbers of functional instream wood. The higher amounts of functional wood may also be associated with the collapse and breakage of wood due to felling and skidding, although no physical evidence of breakage or collapse from harvesting was observed.

The observed results did not support the hypothesis that the streams in wildfire-disturbed sites would have a higher amount (volume and number) of wood compared to the clearcut sites due to the removal of streamside trees during clearcutting. Lower wood amounts in the clearcut streams were not observed, possibly due to contributions from logging slash, the low transport of wood and the long persistence of instream wood. Additional contributions may also be associated with the harvest practices such as cutting and leaving non-merchantable trees with diameters less than 17.5 cm, and prior to the 1980s, lesser valued trees such as subalpine fir *(Abies lasiocarpa*).

5.4.2 Disturbance Effects on Other Instream Wood Characteristics

The finding that the dominant orientation of wood from streams of various widths is perpendicular to streamflow is consistent with other studies (Hogan 1987; Bilby and Ward 1989; Robison and Beschta 1990; Baillie and Davies 2002). This tendency may be associated with the dominant snag fall patterns related to wind patterns, bank undercutting during high flows, and the general tendency for trees to lean across stream channels due to the phototrophic nature of tree growth (Grizzel and Wolff 1998; Baillie and Davies 2002; Bragg and Kershner 2004). The predominance of perpendicular wood pieces also indicates wood stability (Robinson and Beschta 1990; Hogan 1986) since stream channels that have experienced extreme hydrologic or geologic events (e.g. high floods or debris flows) tend to have higher proportions of wood oriented parallel to streamflow (Hogan 1986).

Ralph et al. (1994) found that approximately 33% of wood interacted with the stream at low flows in intensively harvested basins, increasing to 66% in old-growth and unharvested basins. Ralph et al. (1994) attributed this difference to the increased mobility of wood in the harvested basins. In contrast, this study found 50% of the wood in the lower portions of the stream channel for the Harvest 70 category compared to 31% in the

Old Forest category. The higher wood loadings in the lower portion of the stream channel could be attributed to two main factors. First, the small streams have low transport capacity. Second, the majority of wood in the Harvest 70 category was highly decayed and prone to collapse into the lower portions of the stream channel. This further supports the assertion by Jackson and Sturm (2002) that "…large wood relationships should not be extrapolated downward to small streams." Since the majority of streams included in Ralph et al. (1994) were large (bankfull widths 5 to 15 m) and had higher transport capacities, it is not surprising that the relation they found did not translate to this study, which focused on much smaller streams.

5.5 MANAGEMENT IMPLICATIONS

5.5.1 Comparison of Wildfire Disturbance and Clearcut Harvesting

A primary objective of this study was to better understand whether or not clearcut harvesting emulates natural disturbance in relation to instream wood. Similar to other studies (e.g. McCrae et al. 2001; Nitschke 2005), this study found that there were significant differences between streamside clearcut harvesting and wildfires. Major differences between clearcut harvesting and wildfire in relation to old forests were observed in the volume, size, decay state and position of wood. This study only addressed differences in wood attributes over the short-term (< 50 years) subsequent to wildfire or clearcut harvesting, but many of these differences could have long-term implications. For example, increased wood volumes subsequent to wildfire disturbances, coupled with higher volumes present above and spanning the stream channel, can provide a long-term wood supply that can influence pool formation and sediment storage. The increased wood volume also provides important cover for aquatic organisms during regeneration of the adjacent wildfire-disturbed streamside stand. These factors may also provide a long-term legacy of instream wood that can continue to influence stream channels as the streamside forest matures (> 100 years) and may also complement instream wood loads and functions associated with subsequent forest disturbances.

Reduced wood inputs associated with the removal of trees from clearcut harvesting, linked with a reduction in the amount of wood spanning the stream channel and an increased proportion of wood in an advanced state of decay, can reduce the influence of wood on stream channels as the streamside forest matures. Although this study found somewhat subtle differences over the short term, it is likely that the instream wood differences between wildfire disturbed and clearcut harvested streams would be magnified as result of successive harvest rotations (typically 80 to 100 years in this region) in the absence of large episodic inputs of wood. Differences in water chemistry, sediment and summer stream flows have also been observed by other researchers (e.g. Carignan et al. 2000; Lamontagne et al. 2000; Nitschke 2005), further highlighting that the recovery of wood after clearcut harvesting can follow a different trajectory than wildfire. If the intent of forest management is to emulate natural patterns and processes, then riparian management strategies have to ensure suitable levels of instream wood supply are met over the long-term to maintain ecological function, complexity and diversity in aquatic ecosystems (Attiwill 1994; Resh et al. 1988; Bisson et al. 2003).

5.5.2 Reference Loads or Targets

The abundance and volume of wood in streams flowing through old growth forests have been described as a baseline reference loading for forest management planning, habitat restoration and monitoring of stream condition (Lisle 2002; Fox et al. 2003). In this study, key variables (number of pieces and volumes) were similar between streams that flowed through areas affected by streamside clearcuts and those that flowed through undisturbed older riparian forests, suggesting that stream conditions associated with these wood parameters may also appear to be very similar. However, two important differences were identified.

First, a large proportion of wood in the two harvested forest categories was well decayed as compared to the older Old Forest (reference) sites. This degree of decay was particularly apparent in the streams that flowed through riparian areas that had been harvested approximately 30 years ago. Wood in this advanced state of decay is more susceptible to physical fragmentation and will eventually have a reduced role in influencing aquatic habitat and stream channel morphology. Although this susceptibility to change depends upon the inherent stability of the channel in the absence of wood, any long-term reductions in wood could result in the loss of habitat and cover. Over the long-term the decay of instream wood could also be influenced by riparian management strategies that are focused on the regeneration of one tree species over another since the persistence of wood is dependent upon species (Harmon et al. 1986). For example, lodgepole pine has a residency time of about 80 years and decays much faster than spruce species, which have a residence time up to 150 years (Powell 2006).

A second and related difference between the harvested and the Old Forest sites involved the amount of wood situated above bankfull height that spanned the stream channel. Compared to the Old Forest sites, the older harvested areas had less wood spanning the channels, thus reducing the amount of wood directly available for contribution to the stream channel. The reduction of wood supply for recruitment could have implications for future aquatic condition including channel morphology over longer time scales. Thus, the development of reference loadings (Lisle 2002) or wood "targets" (Fox et al. 2003) for the assessment of harvesting effects requires not only the number and volume of wood pieces but also consideration of wood condition, function and position.

5.6 CONCLUSION

Natural disturbances such as wildfire have been recognized as an important element in maintaining ecological functions, complexity and diversity in both forest and aquatic ecosystems. Improved understanding of the similarities and differences between timber harvesting and wildfire disturbance is a critical element in today's forest management paradigm of ecosystem-based management. This study found that wildfires and clearcut harvesting affect the volume, distribution and characteristics of wood in small streams of south-central British Columbia in four ways: (1) Higher wood volumes are present in small streams within 50 years after wildfire disturbances, confirming the importance of wildfires as an important mechanism for wood recruitment. (2) Streamside clearcut harvesting does not immediately (<30-40 years) result in reduced wood loads in streams that have relatively low transport capacities, especially if harvest practices are designed to maintain existing instream wood supplies prior to harvest. (3) Wood loading reflects a complex inter-play between forest stand dynamic factors such as disturbance history (e.g. frequency of wildfire disturbances), patterns of forest succession, episodic wood inputs and chronic wood inputs (e.g. logging slash, windthrow, bank erosion and slow decay). These factors may conceal differences in wood loading between disturbance categories. (4) Counts of wood number and volume in themselves do not provide a full description of instream wood. Wood characteristics such as decay state, position and geomorphic function are also required to fully appreciate instream wood changes associated with disturbances especially over longer time scales.

Table 5.1. Comparison of sample streams and riparian forest stand (pre and post-disturbance) characteristics of the four disturbance categories.

	Old Forest Mean ± SD (range)	**Wildfire Mean ± SD (range)**	**Harvest 90 Mean ± SD (range)**	**Harvest 70 Mean ± SD (range)**	**F or Chi-Square**	**p value**	**Multiple Comparison of Means (Significant Differences)**
Number of Sample Streams	8	6	7	5			
Bankfull Width (m)	2.5 ± 0.6 (1.6-3.4)	2.5 ± 0.8 (1.4-3.4)	2.0 ± 0.8 (1.3-3.5)	2.4 ± 0.5 (1.9-3.1)	0.73	0.55	
Bankfull Depth (cm)	48 ± 9 (36-62)	47 ± 4 (40-51)	36 ± 5 (29-43)	46 ± 6 (36-52)	4.97	<0.01	Harvest 90 > Old Forest, Wildfire, Harvest 70
Gradient (%)	4.9 ± 2.3 (1.1-7.8)	6.4 ± 1.5 (3.9-8.0)	7.4 ± 4.2 (3.3-15)	6.0 ± 2.9 (3.8-11)	0.94	0.44	
Drainage Area (ha)	402 ± 245 (231-942)	460 ± 288 (175-837)	488 ± 388 (156-1256)	505 ± 224 (308-868)	0.03	0.99	
Current Stand Age (years)	166 ± 31 (120-200)	40 ± 9 (32-50)	13 ± 0.5 (12-13)	32 ± 5 (27-37)	110.9	<0.01	
Predisturbance Stand Age (years)*	166 ± 31 (120-200)	157 ± 58 (102-215)	118 ± 34 (84-176)	134 ± 36 (97-184)	2.05	0.14	
Predisturbance Tree Density (stems/ha)*	1144 ± 371 (750-1850)	691 ± 242 (500-1000)	621 ± 310 (300-1200)	620 ± 292 (400-1100)	4.73	0.01	Old Forest > Harvest 90, Harvest 70
Predisturbance Basal Area (m^2/ha)*	58 ± 16 (39-85)	47 ± 1.7 (46-50)	58 ± 25 (21-89)	54 ± 11 (44-70)	0.65	0.59	
Current Tree Density (Stems/ha) **	1144 ± 371 (750-1850)	483 ± 469 (0-1000)	0 ± 0	320 ± 115 (150-400)	12.5**	<0.01	
Current Basal Area (m^2/ha) **	58 ± 16 (39-85)	17 ± 15 (0-37)	0 ± 0	0.1 ± 0.04 (0.1-0.2)	18.4**	<0.01	
Snags Density (#/ha) **	218 ± 153 (0-550)	67 ± 68 (0-150)	0 ± 0	0 ± 0	17.4**	<0.01	

*Current stand conditions are used for the Old Forest category.
**Due to unequal variance the Kruskal-Wallis rank sum test was used to test whether means are the same across the four disturbance categories.

Table 5.2. Summary of study streams used to evaluate wood loading in relation to the four disturbance categories.

Stream	Disturbance Category	Harvest Date (years)	Gradient (%)	Mean Bankfull Width (m)	Median Piece Diameter (cm)	Median Piece Length (m)	Total No. of Wood (# /100 m)	Functional No. of Wood (#/ 100 m)	Total Wood Volume (m^3/100 m^2)	Functional Wood Volume (m^3/100 m^2)
MUNCRK1	Old Forest	-	7	2.0	15	1.9	50	34	1.0	0.6
REED1	Old Forest	-	5	2.4	15	2.1	50	18	1.3	0.4
MUNCRK2	Old Forest	-	2	3.4	12	2.3	61	41	0.8	0.5
DOME1	Old Forest	-	1	2.1	16	2.0	40	27	1.2	0.8
DOME2	Old Forest	-	8	2.8	15	2.6	49	21	1.4	0.4
LOWERCORP	Old Forest	-	4	2.9	14	2.3	97	15	2.3	0.6
DARLEY	Old Forest	-	7	3.0	15	2.3	100	30	2.5	1.2
NICTRIB	Old Forest	-	2	1.6	16	1.7	17	11	0.8	0.5
PASAYTEN1	Wildfire		8	3.2	20	2.6	90	38	4.5	2.0
PASAYTEN2	Wildfire	-	7	2.9	20	2.6	119	31	5.8	2.0
HIDDEN	Wildfire	-	8	2.4	22	2.3	52	21	7.3	5.3
CANYON	Wildfire	-	6	3.4	22	2.5	31	25	1.6	1.0
CANTRIB1	Wildfire	-	4	1.6	18	1.7	50	42	1.4	1.2
SEL1	Wildfire	-	6	1.4	17	1.8	93	49	6.1	3.6
PEACH1	Harvest 90	1992	14	1.3	13	2.5	51	33	1.3	0.8
PEACH2	Harvest 90	1992	9	1.6	13	1.8	95	35	2.4	1.0
UWKRAB3	Harvest 90	1993	3	2.4	16	2.7	93	58	2.9	2.1
LAMBLY1	Harvest 90	1992	10	2.2	18	2.3	41	37	1.8	1.5
LAMBLY2	Harvest 90	1992	7	1.4	15	1.9	93	84	3.7	3.2
CHRIS1	Harvest 90	1993	4	1.9	16	2.0	92	73	4.3	3.2
GOLD1	Harvest 90	1992	4	3.5	18	2.6	70	56	2.1	1.6
UWKRAB1	Harvest 70	1973	5	2.4	16	2.2	58	45	1.6	1.2
UWKRAB2	Harvest 70	1978	4	3	15	2.5	39	30	0.8	0.6
CRESTREB1	Harvest 70	1977	11	2	13	2.3	78	65	2.4	2.2
UNTRT1	Harvest 70	1969	4	2	14	1.8	87	51	2.1	1.1
TERRACE1	Harvest 70	1968	6	3	16	2.0	117	104	4.7	4.5

Table 5.3. Comparison of total and functional wood storage (number and volume) between disturbance categories.

	Disturbance Category	Category Mean	Standard Deviation	n	F ratio	P value	Multiple Comparison of Means (Significant Differences)
Total Number (# / 100 m)	Harvest 90	75	22	7	0.65 d.f. = 3,22	0.59	
	Harvest 70	76	30	5			
	Old Forest	58	28	8			
	Wildfire	73	33	6			
Functional Number (#/ 100 m)	Harvest 90	54	20	7	5.58 d.f. = 3,22	<0.01	Harvest 90 and Harvest 70 > Old Forest
	Harvest 70	59	28	5			
	Old Forest	25	10	8			
	Wildfire	34	10	6			
Total Volume (m^3/100 m^2)*	Harvest 90	2.4	1.5	7	4.92 d.f.= 3,22	<0.01	Wildfire > Old Forest
	Harvest 70	2.0	1.9	5			
	Old Forest	1.3	1.5	8			
	Wildfire	3.8	2.0	6			
Functional Volume (m^3/100 m^2)*	Harvest 90	1.7	1.7	7	9.21 d.f. = 3,22	<0.01	Wildfire, Harvest 90 and Harvest 70 > Old Forest
	Harvest 70	1.5	2.1	5			
	Old Forest	0.6	1.4	8			
	Wildfire	2.3	1.7	6			

* Means and standard deviations are untransformed values, but the test statistic was calculated using a log transformation.

Table 5.4. Summary of two factor analysis of variance for total volume (log transformation) after accounting for the interaction between the disturbance categories and the two orientation classes (Perpendicular or Parallel) (Adj. $r^2 = 0.44$).

	DF	F ratio	p value
Whole Model	7	6.61	<0.001
Disturbance Category	3	10.51	<0.001
Orientation Class	1	11.16	0.002
Disturbance Category x Orientation Class	3	0.60	0.617

Table 5.5. Summary of two factor analysis of variance for total volume (log transformation) after accounting for the interaction between the disturbance categories and the three position categories (Adj. $r^2 = 0.0.32$).

	DF	F ratio	p value
Whole Model	11	4.29	<0.001
Disturbance Category	3	7.70	<0.001
Position Category	2	2.82	0.067
Disturbance Category x Position Category	6	3.18	0.008

Table 5.6. Summary of two factor analysis of variance for total volume (cube root transformation) after accounting for the interaction between the disturbance categories and decay classes (Adj. $r^2 = 0.77$).

	DF	F ratio	p value
Whole Model	11	24.13	<0.001
Disturbance Category	3	4.75	0.005
Decay Class	2	112.22	<0.001
Disturbance Category x Decay Class	6	7.12	<0.001

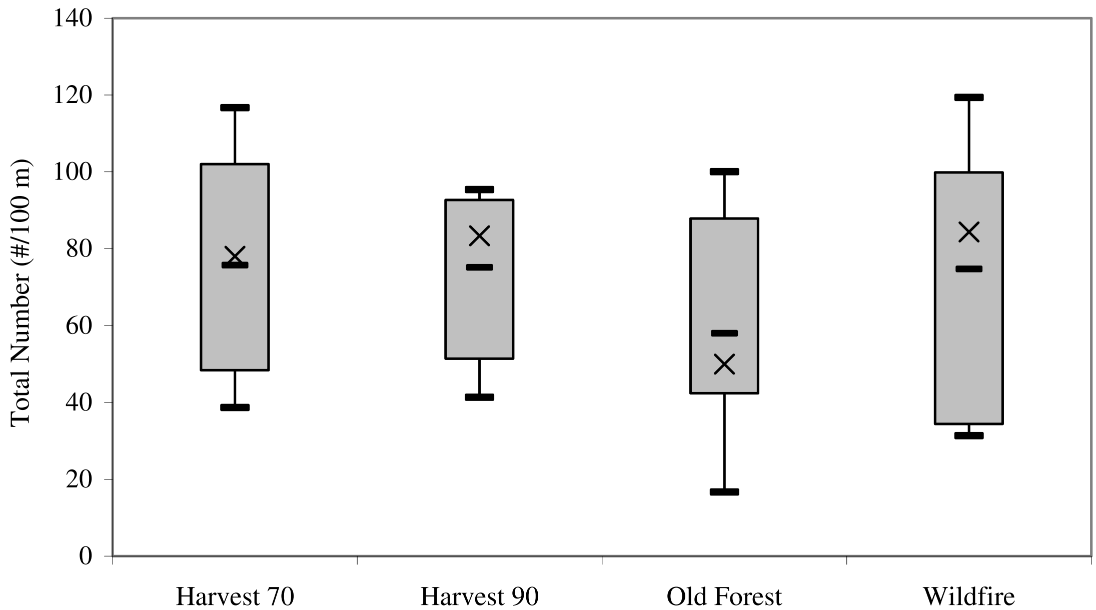


Figure 5.1. Box plot showing the total number of wood pieces in each of the four disturbance categories. In the box plot, means are represented as crosses, medians are represented as a line, bars represent upper and lower quartiles and whiskers denote the range.

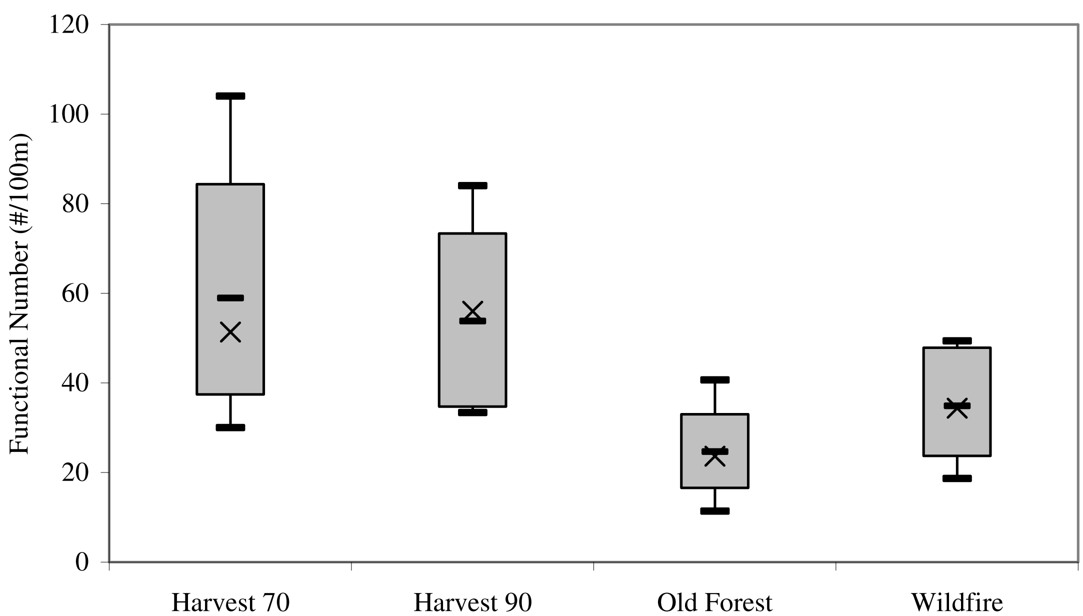


Figure 5.2. Box plot showing the functional number of wood pieces in each of the four disturbance categories. See Figure 5.1 caption for explanation of box plots.

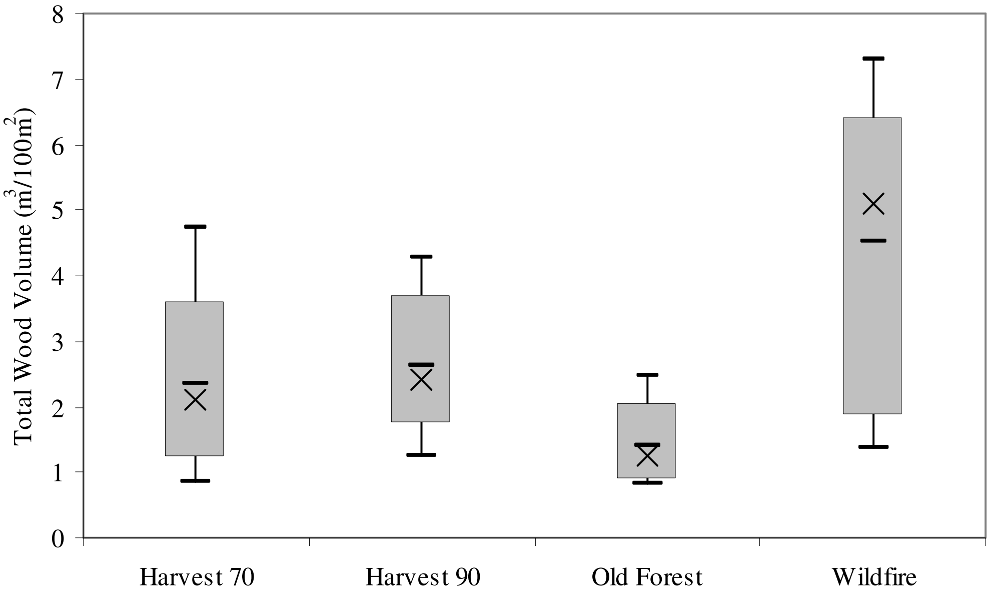


Figure 5.3. Box plot showing the total volume of wood for each of the four disturbance categories. See Figure 5.1 caption for explanation of box plots.

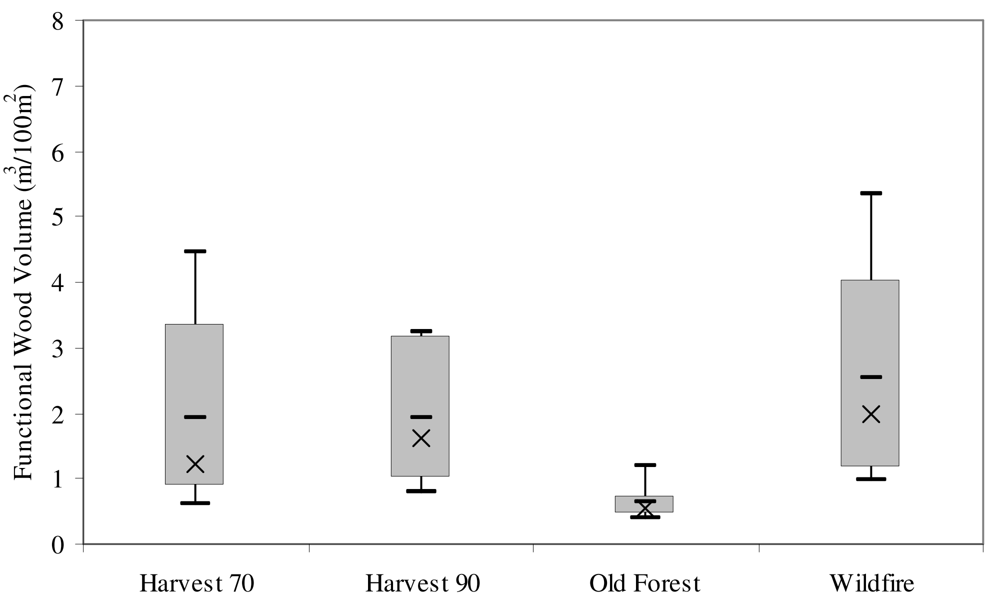


Figure 5.4. Box plot showing the functional volume of wood for each of the four disturbance categories. See Figure 5.1 caption for explanation of box plots.

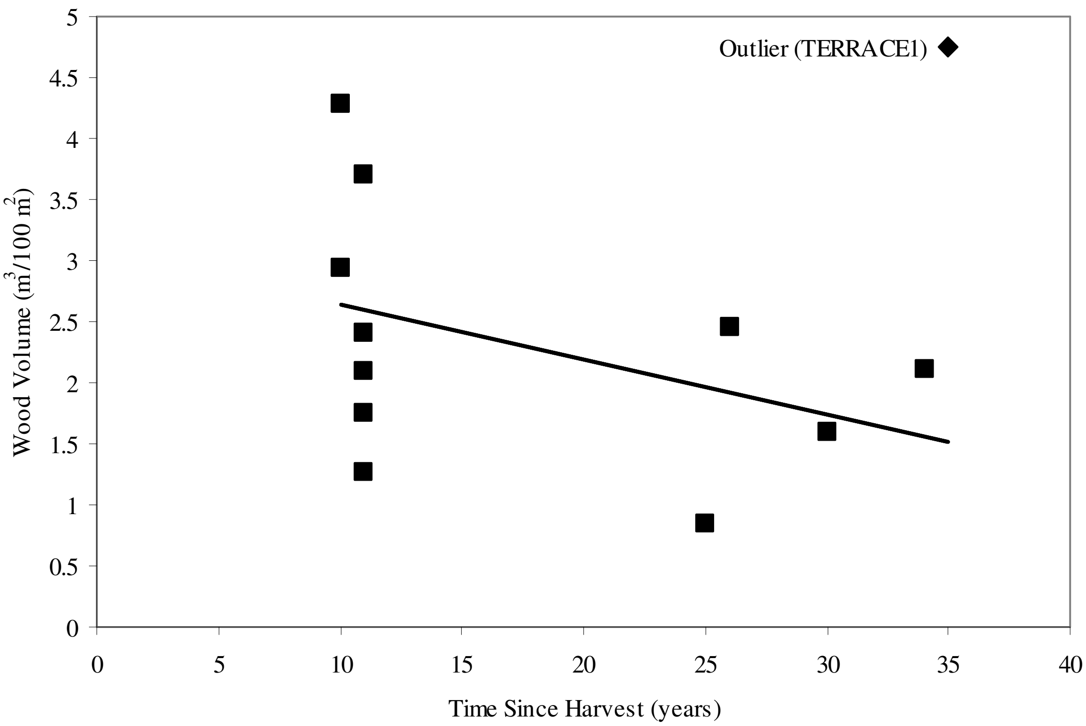


Figure 5.5. Instream wood volume (m^3/100 m^2) for harvested sites in relation to time since harvest (years). Decreasing linear trend with outlier removed was not significant ($F_{1,9}$ = 1.83, p = 0.209, Adj r^2 = 0.08).

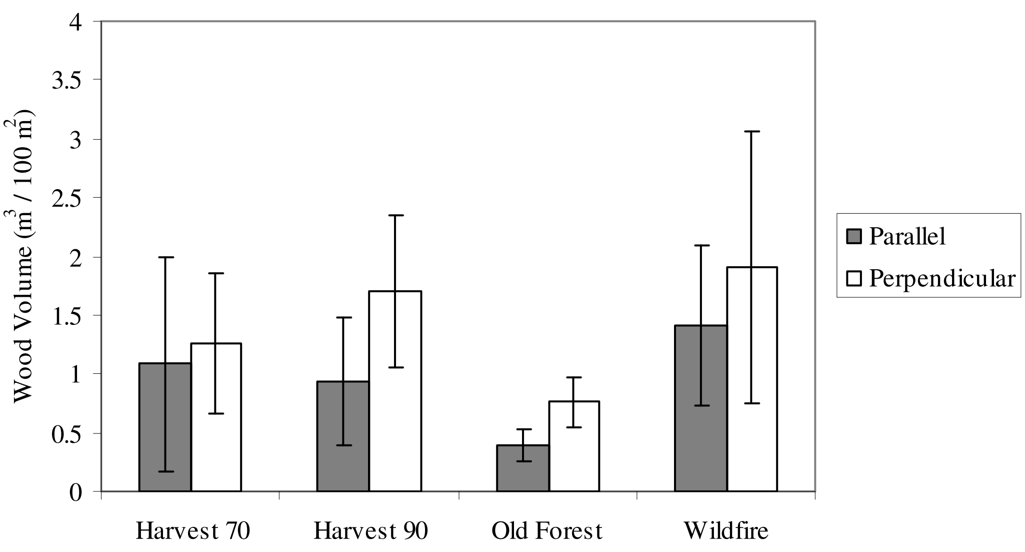


Figure 5.6. Orientation of wood in the four disturbance categories (parallel or close to parallel (315-45°,135-225°); perpendicular or close to perpendicular (45-135°/ 225-315°). Error bars indicate one standard deviation. No significant differences in wood volumes between orientation categories were found.

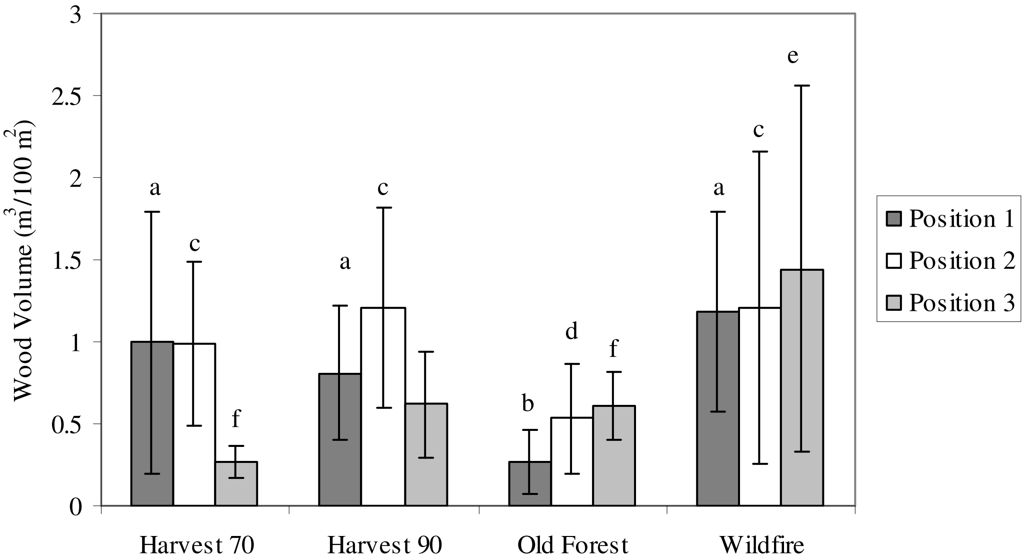


Figure 5.7. Position of wood pieces in the four disturbance categories. Error bars indicate one standard deviation. Three positions are: (1) wood that is entirely situated below bankfull height; (2) wood that intersects bankfull height and is situated both below and above bankfull height; and, (3) wood that is entirely above bankfull height. Significant differences in wood volumes within each position category are denoted with letters (i.e. a > b, c > d and e > f). Significant differences are based on the interaction between the disturbance categories and position categories.

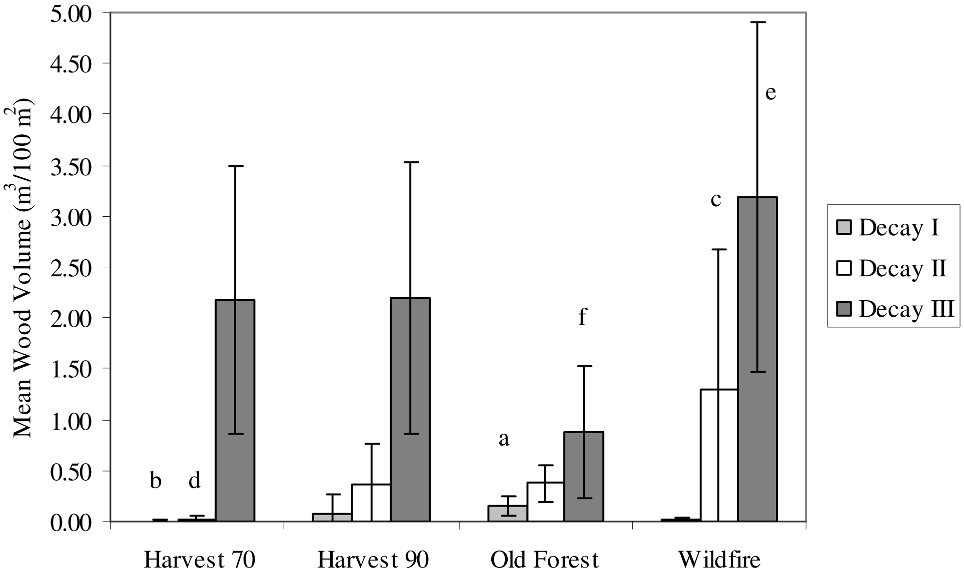


Figure 5.8. Mean wood volume ($m^3/100\ m^2$) by Decay Class in the four disturbance categories. Error bars indicate one standard deviation. Significant differences in wood volumes in each Decay Class denoted with letters (i.e. a > b, c > d and e > f).

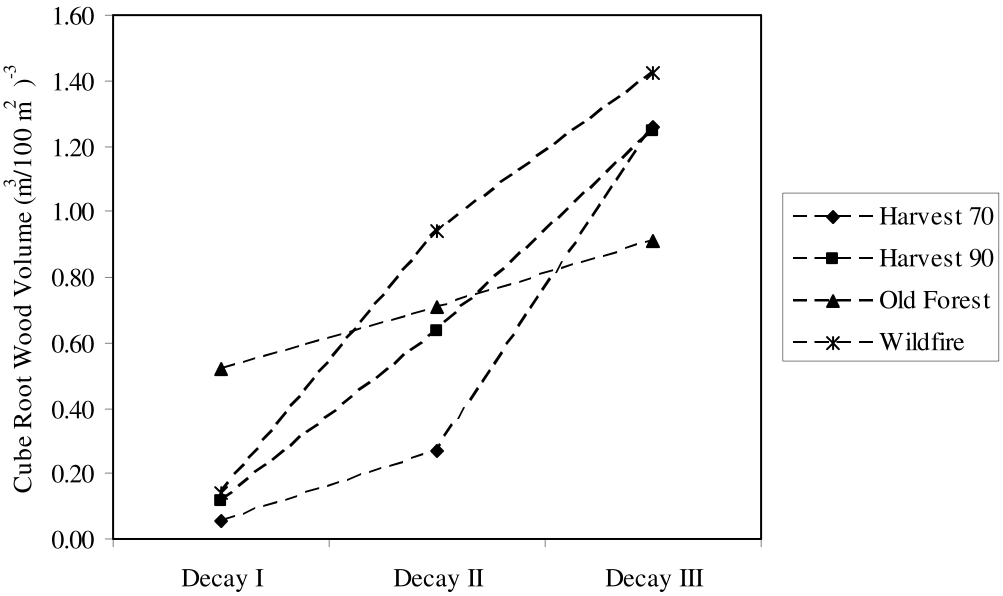


Figure 5.9. Interaction plot showing wood volume (transformed using cube root) and the factor effects of the Disturbance Category and Decay Class. Note: the difference in slope between the OF category and the remaining three disturbance categories indicates significantly different wood volumes in the OF category as compared with the remaining three categories after accounting for differences in wood volume between the disturbance categories.

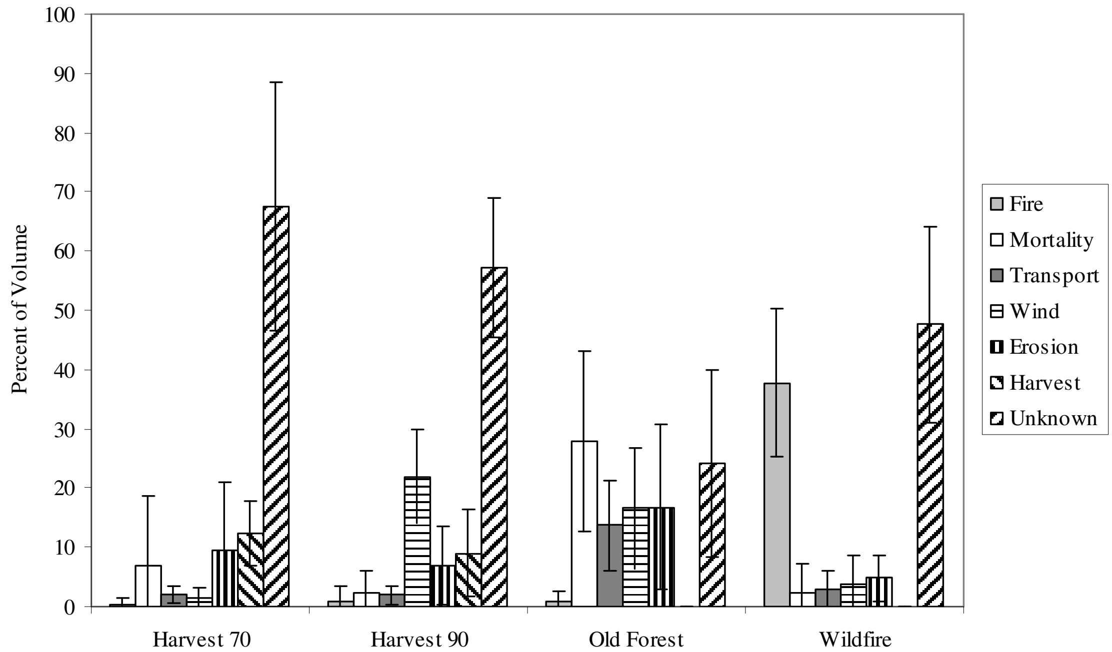


Figure 5.10 Input source (percent of volume) for each of the four disturbance categories. Standard deviations indicated by error bars.

CHAPTER 6
INFLUENCE OF STAND REPLACING WILDFIRES AND STREAMSIDE CLEARCUT HARVESTING ON SMALL STREAM CHANNEL MORPHOLOGY

This chapter is focused on a detailed comparison of the effects of wildfire and streamside clearcut harvesting on channel morphology. This chapter incorporates the wood quantity measurements, disturbance categories and stand development stages utilized in Chapters 4 and 5.

6.1 INTRODUCTION

The physical nature and morphology of streams are governed by many processes (Church 1992; Church and Ryder 2001), including the volume and timing of streamflow, the volume, timing and character of sediment inputs, the nature of the materials through which the streams flow, the gradient over which water flows, local geologic history of the landscape, local climate and the state of riparian vegetation (Church 1992; Church and Ryder 2001). Anthropogenic or natural disturbances such as streamside clearcut harvesting or wildfire can influence the physical nature and morphology of streams mainly through alteration of four of these governing processes: streamflow (i.e. magnitude, intensity and frequency), sediment (volume and character), riparian vegetation and the nature of material through which a stream flows (e.g. instream wood) (Montgomery and Buffington 1997, Wohl 2000). Physical alterations to stream channels can affect aquatic habitat and can be locally detrimental to populations of aquatic organisms. Fish, amphibians and macroinvertebrates can all be negatively affected through the loss or reduction in quality of habitat, decreased water quality, modified flow patterns and through the loss of cover (Bisson et al. 1987; Bilby and Bisson 1998).

Potential alterations in the physical nature and morphology of channels as a result of disturbances occur at many different temporal and spatial scales (Gregory et al. 1991). Temporal scales include chronic processes occurring regularly from months to years and episodic or catastrophic alterations occurring infrequently from decades to centuries (Gregory et al. 1991). Spatial scales include localized alterations of stream channels (e.g. channel widening) involving relatively small changes of a few centimetres or square meters to larger sub-basin or watershed scale alterations that affect several channel reaches or entire stream networks (e.g. large floods or debris torrents) (Gregory et al. 1991). These processes can be arbitrarily divided into direct effects, which occur at the stream reach scale, or indirect cumulative effects, which occur at a watershed or sub-basin scale downstream of a disturbance (Reiter and Beschta 1995).

Streamside clearcut harvesting can have direct effects on channel morphology, including channel widening (Beschta 1998), increased riffle habitat due to scour or sedimentation (Hogan 1986; Hogan et al. 1998), and reduced pool habitat (Hogan 1986; Ralph et al. 1994; Wood-Smith and Buffington 1996). Similar responses have also been observed in stream channels disturbed by wildfire (e.g. Minshall et al. 1997; Legleiter et al. 2003; Zelt and Wohl 2004). Few, if any of these studies, have compared changes in the physical nature and morphology of channels between streamside clearcut harvesting and wildfire disturbances. Also, the majority of past studies have been conducted in relatively large order (i.e. > 3^{rd} order) stream channels and channel morphology types that are generally considered to be most sensitive to disturbances (Hassan et al. 2005a).

Furthermore, limited research has focused on the recovery (or deterioration) of stream channel morphology through time subsequent to streamside clearcut harvesting or wildfire. As described in earlier chapters, some research has examined the temporal aspects of wood loading subsequent to wildfire or forest harvesting (e.g. Bragg 2000; Benda and Sias 2003), but limited research has focused on the temporal changes in the physical nature and morphology of stream channels linked with changes in wood loading through time. Research focused on understanding the temporal changes in the physical nature and morphology of channels is critical to better describe the recovery and resiliency of various channel morphologies to different forest disturbances.

This chapter has two main objectives. The first is to document the direct effects of streamside clearcut harvesting and wildfire disturbances on the physical nature and morphology of several small (< 3^{rd} order) streams. The second is to explore how the physical nature and morphology of several small streams vary through time since the last major wildfire disturbances, in response to post-disturbance stand development.

This chapter addressed the following hypotheses:

1. Channel morphology characteristics in small streams are influenced by wood abundance and volume.

2. Channel morphology characteristics are altered as result of streamside clearcut harvesting or wildfire disturbance as compared to streams flowing through unharvested older riparian forest stands.
3. Channel morphology characteristics change in relation to stand development stage and in association with the time since the occurrence of major wildfire disturbances.

6.2 METHODS

6.2.1 Field Methods

This investigation includes an evaluation of various channel morphology characteristics collected from all 38 streams that were described in the preceding chapters. In conjunction with wood quantity measurements described in earlier chapters, several channel morphology characteristics in the 150 m study reaches were measured utilizing the approach developed by Kaufmann and Robison (1998). Bankfull width, bankfull depth, gradient and bed particle size distributions were collected at 11 cross-sections placed at equal intervals (i.e. 4 - 5 bankfull widths) along the study reaches. Bankfull width and depth were defined by a change in vegetation (e.g. from no moss cover to moss-covered ground) and a topographic break from the channel bank to the forest floor. Width and depth measurements were measured with a metal logger's tape and channel gradient was determined with a Suunto handheld clinometer.

The number of particles smaller than 8 mm was calculated for each study stream using the zig-zag pebble count procedure developed by Bevenger and King (1995) modified from the procedure developed by Wolman (1954). At each of the 11 cross-sections the b-axis diameter of 10 particles (i.e. 110 particles measured per 150 m segment) were measured to the nearest millimetre at approximately one-meter intervals while traversing diagonally upstream between channel banks. A particle size of 8 mm was used as an upper threshold because forest management activities (e.g. roads) have been shown to significantly increase the amount of fine sediment (<8 mm) (Bevenger and King 1995; Schnakenberg and MacDonald 1998). In addition, this particle size represents a break in (log 2) phi class and is considered to be the threshold that is detrimental to many coldwater fish species (Schnakenberg and MacDonald 1998). A visual estimate of the largest stone moved (D) by flowing water was also determined at each cross-section (BC Ministry of Forests, 1996). Similar to Mellina et al. (2005), D was used as surrogate for stream power since it represents the stream's ability to transport particles.

Channel unit type, pool type and thalweg depth were measured at 1 m intervals longitudinally along the study reaches. Channel unit types (Table 6.1) were described as pools, glides, riffles, rapids, cascades and falls utilizing the approach developed by Kaufmann and Robison (1998) as a modification from Bisson et al. (1982) and Frissell et al. (1986). The processes that created the pools were also categorized into five groups: impoundment, plunge, lateral, trench or backwater. The key elements that formed the pools were identified as wood, boulder/bedrock or fluvial. These pool-forming processes and elements were compared between the four disturbance categories and the four stand development stages described in Chapters 4 and 5. The thalweg depths were used to calculate residual pool size characteristics. All field measurements were collected during baseflow conditions during the months of August to October.

6.2.2 Data Analysis

The above field measurements were used to generate ten channel morphology characteristics. The characteristics included:

- total pool length (m / 100 m)
- ratio of pools formed by wood (m / 100 m)
- pool spacing (bankfull widths / pool),
- average pool / riffle ratio (m / m),
- bankfull width coefficient of variation (%),
- average residual pool depth (m)
- maximum residual pool depth (m)
- total longitudinal residual pool area, "sagittal area" (m^2 / 100 m)
- total residual pool volume (m^3 / 100 m)
- number of deep pools (# / 100 m)

Total pool length was calculated by adding the total length of pools within the study reach. The ratio of pools formed by wood was calculated by dividing the total number of pools identified to be formed by wood divided by the total number of pools within the study reach. The pool spacing in each study reach was calculated similar to the approach used by Montgomery et al. (1995) by dividing the reach length by both the number of pools and average channel width. Similar to Hogan (1986) and Hogan et al. (1998) the average pool/riffle ratio was calculated as:

$$P/R = \sum_{i=1}^{n} L_{P_i} \bigg/ \sum_{i=1}^{n} L_{R_i} \qquad (6.1)$$

where n = number of pools (*P*) or riffles (*R*) and L = length of Pool or Riffle. The coefficient of variation for bankfull width was expressed as a percentage by dividing the standard deviation of the channel widths collected from the eleven cross-sections by the mean channel width for each study reach.

Residual Pool Measurements

The thalweg depths were used to calculate residual pool characteristics following the rapid streambed profile (RSP) approach developed by Stack (1989), Stack and Beschta (1989), Robison and Kaufmann (1994) and further evaluated by Robison (1997). Residual pool measurements are considered to be flow-independent and are, therefore, subject to less observer bias than more subjective flow-dependent measurements such as visual pool classifications (Lisle 1987, Kaufmann and Robison 1998). The RSP has been described as an efficient (time and money) and effective (reproducible) approach (Stack and Beschta 1989) to defining pools in small streams with close agreement reported by Robison and Kaufmann (1994) and Robison (1997) to the more rigorous and time-consuming thalweg bed elevation procedure (BEP) that utilize bed elevation data. For example, Robison (1997) found a strong correlation (r^2 = 0.96) between the RSP and BEP residual pool area (longitudinal area). A strong relation (r^2 = 0.94) was also observed between the RSP method and the BEP method (refer to Appendix A) for seven streams sampled in this study.

Average residual pool depth was calculated by totaling all calculated residual pool depths by the total number of residual pool depth measurements within each 150 m study reach. Maximum residual pool depth was simply the maximum pool depth measured within each 150 m study reach. Total longitudinal residual pool area and total residual pool volume were simply calculated as the sum of individual pool areas and volumes in each of the study reaches (refer to appendix A for individual pool area and volume calculations). The number of deep pools was the number of pools present where the residual depth exceeded a minimum average bankfull depth of 30 cm in all of the study reaches. This definition is similar to the deep pool definition used by Tripp et al. (2005), where a deep pool is defined as a pool where the depth from the bottom of the pool to the top of the channel is twice the channel depth in the riffle below the pool. The average bankfull depth for all the study reaches consistently ranged from 30 to 50 cm; therefore, pools with residual depths greater than 30 cm would be approximately twice the channel depth and would approximate the deep pool definition used by Tripp et al. (2005).

6.2.3 Statistical analysis

To address the three hypotheses described above, three sets of statistical analyses were conducted. All analyses used the same groupings of study streams (i.e. four disturbance categories and four stand development stages) as described in Chapter 4 and 5.

In the first set of statistical analyses, Analysis of Covariance (ANCOVA) using channel gradient and bankfull width was used to compare the pool types between the four disturbance categories and the four stand development stages. ANCOVA, using total wood abundance and total wood volume as covariates, was also used to evaluate whether potential differences in pool types were related to wood loading. The number of particles smaller than 8 mm in each of the disturbance categories or stand development stages was analyzed using chi-squared contingency tables (Bevenger and King 1995).

The second set of statistical analyses explored the potential differences in the first nine channel morphology characteristics among the four disturbance categories and the four stand development stages using ANCOVA with channel gradient and bankfull width as covariates. As identified by others (e.g. Bilby and Ward 1991, Beechie and Sibley 1997, Gomi 2001) these covariates were used to increase the sensitivity of the test by accounting for variability associated with channel gradient and width. This approach was assumed to account for potential differences in channel types that have been identified as being important in making channel comparisons (Trainor and Church 2003). Interaction terms (i.e. disturbance category x gradient; disturbance category x channel width) were used in all of these ANCOVA tests to test for homogeneity of regression. Homogeneity of variances, normality of distributions and absence of multicollinearity were all checked using residual plots, leverage plots and pairwise correlations (Neter et al. 1996). Where necessary, log transformations were used successfully to correct problems with normality and homogeneity of variance. For the last channel morphology characteristic, the number of deep pools, only descriptive statistics were used to evaluate whether a relation to the disturbance categories or stand development stages was present since very few deep pools were observed in any of the study streams.

The final statistical analyses explored the relation between the first nine channel morphology characteristics and wood quantities by using the all-possible-subsets-regression approach (Neter et al. 1996) to determine the role that wood plays in small stream channel morphology. In this set of analyses the streams within clearcuts were excluded to provide a clearer understanding of the role that wood plays in the study streams in absence of direct anthropogenic influences. Initial models were based on review of scatter plots, residual analysis, diagnostic tests such as Mallow's Cp criteria and log transformations, if required (Neter et al. 1996). Similar to Jackson and Sturm (2002), only explanatory variables with p-values less than 0.05 and a model r^2 values of greater than 0.40 were accepted. Potential explanatory variables included gradient (%), bankfull width (m), bankfull depth (m), basin area (km^2), number of wood pieces / 100 m, wood volume/100 m^2, riparian tree age, and the b-axis diameter (D) of the largest stone moved by flowing water. The response variables included the first nine of the channel morphology characteristics described earlier.

6.3 RESULTS

6.3.1 Channel Morphology in relation to the Disturbance Categories

Channel Units - Channel units in all four disturbance categories were dominated by riffles (41 to 61 m/100 m) with cascades (<1 to 14 m/100 m) covering the shortest length of channel (Figure 6.1). No falls were identified in any of the study streams, which reflects the limited amount of exposed bedrock observed. The length of channels in pools (15 to 20 m/100 m) and glides (24 to 33 m/100 m) were intermediate to the above. Based upon a simple descriptive comparison, no apparent differences in channel unit frequencies appear to be present among the four disturbance categories (Table 6.2, Figure 6.1).

Pool Formation- In three out of four of the disturbance categories (e.g. Harvest 70, Old Forest and Wildfire) impoundment pools were the dominant pool-forming process with plunge pools being dominant in the Harvest 90 category. Combined, plunge pools and impoundment pools encompassed more than 65% of all pools. The frequencies of impoundment, plunge and trench pools did not differ significantly between the four disturbance categories after accounting for the potential influences of channel slope and gradient (Table 6.3). Comparison of lateral pool lengths between the four disturbance categories was inconclusive since the disturbance category x channel slope interaction term was significant and violated the assumption of homogeneity of regression. The length of lateral pools was significantly related to channel slope and width with lower gradients and narrow channels having a higher amount of lateral pools. The length of plunge pools was also related to channel width with a greater length of plunge pools present in narrow channels. Unexpectedly, channel gradient was not related to plunge-pool frequency. In contrast, other researchers (Stack and Beschta 1989, Jackson and Sturm 2002) have suggested a higher occurrence of plunge-pools is related to steeper stream gradients that have greater elevation losses per unit length as compared to lower gradient channels resulting from the concentration of fluvial energy towards the channel bed. This difference may indicate that there is insufficient fluvial energy available to erode channel beds in the steeper stream channels of this study. Also, no differences in pool-forming processes were found between the four disturbance categories after accounting for potential influences related to total wood abundance or volume (Table 6.4).

Pool-Forming Elements - Instream wood was the main influence on pool formation in the disturbance categories, forming 42 to 85% of the pools (Table 6.2). Pool formation in the Old Forest category was also heavily influenced by boulders (33%) and unidentified fluvial processes (21%), which likely related to the substantial amount of particles observed in the boulder size fraction in the Old Forest category as compared to the remaining disturbance categories (see results below).

Particles Smaller than 8 mm - As shown in Figure 6.2 and the contingency table (Table 6.5) the highest number of particles smaller than 8 mm was observed in the older Harvest 70 category and the Wildfire Category followed by the Old Forest and Harvest 90 Categories. The frequency of particles smaller than 8 mm and the four disturbance categories were dependent based on the chi-square test statistic for independence (X^2 = 113.43, $p < 0.001$) that is, the amount of particles smaller than 8 mm is related to disturbance category.

Channel Morphology Characteristics - No significant differences were found between any of the nine channel morphology characteristics and the four disturbance categories after accounting for potential influences of channel gradient and bankfull width (Table 6.6). Consistent with other studies (e.g. Stack and Beschta 1989, Bilby and Ward 1991, Beechie and Sibley 1997, Dahlstrom and Nilsson 2004), total pool length was negatively related to channel gradient and bankfull width. That is, shorter total pool length was associated with steeper and wider channels. Pool/riffle ratio and residual pool area were also negatively related to channel gradient and bankfull channel width. Differences in maximum pool depth between the four disturbance categories were inconclusive since the disturbance category x channel width interaction term was significant. Also, few deep pools (residual pools > 30 cm) were observed in any of the study streams with no apparent relation to disturbance category (Table 6.7).

6.3.2. Channel Morphology in Relation to the Stand Development Stages

Channel Units - Channel units in all four stand development stages were dominated by riffles (41 to 58 m / 100 m) with cascades (<2 to 14 m / 100 m) covering the shortest length of channel. Similar to the above results, no falls were identified in any of the study streams, further highlighting the limited amount of exposed bedrock observed. The lengths of channels in pools (12 to 19 m/100 m) and glides (24 to 30 m/100 m) were intermediate to the length of riffles and cascades. The stand development stages have visually similar channel unit frequencies (Table 6.8, Figure 6.3).

Pool Formation - In all four of the stand development stages, impoundment pools were the dominant pool formation observed. Plunge pools and lateral scour pools were observed to be intermediate with trench pools encompassing the least amount of channel length (Table 6.8). The frequencies of impoundment, lateral scour, plunge and trench pools did not differ significantly between the four stand development stages after accounting for the potential influences of channel slope and gradient (Table 6.9). The length of lateral scour pools was inversely related to channel gradient.

Pool-Forming Elements - A small proportion (7 to 11%) of the total wood volume influenced the formation of pools. Instream wood was the main influence on pool formation in 3 out 4 of the stand development stages with 34 to 79% of pools observed to have been formed by wood (Table 6.8). Boulders were also a major influence on pool formation with 7 to 42% of the observed pools being influenced by boulders. Small wood (<10 cm in diameter or < 1 m in length) and unidentified fluvial processes had the least influence on pool formation.

In addition, no relation was identified between the volume and number of wood pieces associated with pools in relation to the age of adjacent riparian forest stands, indicating that the episodic delivery of wood associated with wildfire disturbances did not influence the formation of pools (Figure 6.4 and 6.5). This was further supported by the fact that no differences in pool forming-processes were found between the four stand development stages after accounting for potential influences related to total wood abundance or volume (Table 6.10).

Particles Smaller than 8 mm - As shown in Figure 6.6 and the contingency table (Table 6.11) the highest number of particles smaller than 8 mm was observed in the study streams recently affected by wildfire, followed by the oldest stand development stage, with the two intermediate stand development stages having the smallest proportions of particles smaller than 8 mm. The frequency of particles smaller than 8 mm and the four stand development stages were dependent based on the chi-square test statistic for independence (X^2 = 84.05, $p < 0.001$); therefore, the frequency of particles smaller than 8 mm is related to stand development stage.

Stand Development Stages and Channel Morphology Characteristics - No significant differences were found between any of the nine channel morphology characteristics and the four forest stand development stages after accounting for potential influences of channel gradient and bankfull width (Table 6.12). Similar to the earlier analysis regarding the disturbance categories, total pool length and pool / riffle ratio were both negatively related to channel gradient and bankfull width. In relation to the stand development stages, coefficient of variation for bankfull width was negatively related to channel width, indicating that wider channels were more uniform in width than smaller channels. Similar to the analysis of disturbance categories, few deep pools (residual pools > 30 cm depth) were observed in the four stand development stages (Table 6.13).

6.3.3 Channel Morphology and Wood Relations

Based upon the all-possible-subset-regression approach, very few of the channel morphology and wood loading characteristics were found to explain the variation in the nine channel morphology response variables (Table 6.14). Only three out of the nine regressions were significant with r^2-values greater than 0.4. The most common significant explanatory variables were channel width and gradient. Wood abundance only explained the variation in one of the response variables, the length of pools formed by wood. The length of pools formed by wood was positively related to the number of wood pieces and negatively related to bankfull width. Intuitively this makes sense since the higher the abundance of wood, the higher the probability of wood influencing pool formation. It can also be argued that wood is more likely to force pools in wider channels since wood is less likely to span the channel above bankfull height. This results in a higher proportion of wood in contact with channel modifying flows that typically occur at or just above bankfull height. The remaining two response variables that were considered significant were total pool length and the pool / riffle ratio. Both of these response variables were negatively related to channel gradient and bankfull width but were not influenced by volume of wood in the channel.

6.4 DISCUSSION

6.4.1 Channel Morphology in relation to Streamside Clearcut Harvesting

In this study, few channel morphology differences were observed to be significantly related to streamside clearcut harvesting. At a first glance this finding is somewhat surprising given the amount of past literature (e.g. Zimmerman et al. 1967; Swanson et al 1976, Marston 1982; Bisson and Sidell 1982; Bisson et al 1987, Robison and Beschta 1990, Dahlstrom and Nilsson 2004; Davies et al. 2005) that has documented channel changes in association with forest harvesting. However, upon closer inspection of available literature, other studies have shown minimal to no change in channel morphology in association with streamside clearcut harvesting (Carlson et al. 1990; Robison 1997, Jackson and Sturm 2002; Chatwin et al. 2001; Mellina and Hinch unpublished data).

The interplay of several factors related to forest management can help explain the apparent contradictions among these studies and the apparent lack of channel morphology change observed in this study. Some of the main factors include the effects that forest management has on the frequency and occurrence of mass wasting events (e.g. debris torrents, debris flows, landslides or snow avalanches), history of stream cleaning and harvest practices, inherent sensitivity of stream channels to disturbance, changes in stream wood loads and time since harvest.

Frequency and Occurrence of Mass Wasting - An increased frequency and magnitude of mass wasting events subsequent to forest harvesting and roads has been observed in many forest regions (Benda et al. 2005; Hassan et al. 2005b), which in turn can alter "… the balance between sediment supply and transport in stream channels, thereby changing the channel morphology" (Hassan et al. 2005b). Potential channel morphology changes include bank erosion and channel widening, streambed aggradation or degradation, altered bed composition (e.g. fining of bed material), infilling of pools and altered instream wood loading or function. In the literature the most significant changes to channel morphology are related to altered sediment supplies from forest development related mass wasting events (e.g. Gomi et al. 2001). Most typically, small streams are particularly susceptible to mass wasting and channel morphology changes since these channels are coupled directly to steep hillslopes (Church and Ryder 2001); however, an important exception occurs in the Okanagan Highlands and Thompson Plateau, where small streams are situated on relatively modest relief (Church and Ryder 2001) characterized by decoupled hillslopes and highly infrequent landslides. Hence, major alterations in channel morphology due to an altered balance between sediment supply and transport as result of increased mass wasting is rare in the area encompassed by this study.

History of Stream Cleaning and Harvest Practices - The history of stream cleaning and harvest practices are another important consideration that can lead to alteration of channel morphology. In the 1970s and 1980s, removal of logging debris along with pre-existing instream wood was often mandated subsequent to logging to ensure passage of anadromous fish in the Pacific Northwest (Bilby 1984). Stream cleaning has been attributed to channel morphology changes in past studies (e.g. Slaney et al. 1977, Bilby and Ward 1991; Montgomery et al. 2003) and has recently been identified as the common forest management related attribute that explains severe impacts to the physical nature of streams (Mellina and Hinch unpublished data). Mellina and Hinch's (unpublished data) conclusion was based on a meta-analysis of 25 previously published studies conducted throughout Canada and the United States. In my study streams, no such activities or requirements for stream cleaning are known to have existed based on local knowledge and the absence of anadromous salmonid species, as well as the lack of visual evidence of stream cleaning (e.g. bucked logs in or along the channel). As identified by Hassan et al. (2005a), wood in small streams is likely to persist for up to 100 years in absence of mass wasting events since these channels are too small to transport wood. In the absence of stream cleaning, similar persistence of wood is likely, and subtle or insignificant channel morphology changes could be expected given that wood has been shown to be a primary factor in controlling channel stability and the spatial and temporal dynamics of sediment (Bilby and Ward 1989; Montgomery and Buffington 1997).

The nature of past harvest practices can also have a major influence on channel morphology. For example, falling and skidding practices conducted without regard for stream channels (e.g. skidding along stream beds) can negatively impact channel morphology (Chamberlin et al. 1991). In this study, limited evidence is available regarding the manner in which streamside clearcut harvesting was conducted in the 1960s and 1970s; however, there was no direct evidence (e.g. bank erosion or excessive rutting from machines) to suggest that past harvest activities were excessively severe. In the 1990s the Okanagan Timber Harvest Guidelines (BC Ministry of Forests 1992) were in effect, and these guidelines provided important measures in protecting streams (e.g. no-machine buffers within 20 m of streams, retention of non-merchantable vegetation within no-machine buffers) and likely minimized the direct effects of harvest practices on the small streams in this study.

Sensitivity of Stream Channels - Another important factor that dictates whether channel morphology is altered subsequent to forest harvesting is the inherent stability or sensitivity of stream channels to disturbance. For example, Montgomery and Buffington (1997) provided a conceptual framework that describes the influence that channel type (e.g. pool-riffle, plane-bed, step-pool, cascade and bedrock) has on reach level channel morphology characteristics in response to altered sediment supply, wood loading or discharge. In their study, the response of several channel characteristics was rated as likely, possible and unlikely. Reach level characteristics included channel width, depth, roughness, scour depth, grain size, slope and sediment storage. The majority of streams in this study were step-pool and cascade channels based on Montgomery and Buffington's (1997) classification. Montgomery and Buffington (1997) suggested these two channel types are relatively "resilient" to channel morphology change with the potential for channel widening and incision rated as unlikely. However, potential (i.e. possible) channel response in bedform frequency and geometry, grain size and pool scour depths is possible in step-pool channels with only textural changes (i.e. roughness and grain size) possible in cascade channels (Montgomery and Buffington 1997). This study supports Montgomery and Buffington's (1997) conceptual framework, especially since the main difference observed among the oldest streamside-harvested study streams and the unharvested streams was a notable difference in finer particle sizes. In addition, stream power in these streams is low and likely prevented significant pool scour or modifications in channel morphology (Jackson and Sturm 2002).

Wood Load and Channel Morphology Relations - Numerous studies have shown a direct relation between instream wood loads and channel morphology structure since instream wood plays a critical role in regulating sediment transport and diversifying channel form (Bilby and Likens 1980; Bisson et al. 1987; Bilby and Ward 1989, Gomi et al. 2001). As described in Chapter 5, no significant decreases in wood loading (frequency and volume) were observed between the clearcut harvested and old forest streams; therefore, detectable changes in channel morphology associated with wood would also not be expected. Even if loss of wood was detected significant changes in channel morphology would likely be difficult to detect since step-pool and cascade type channels are generally resilient to changes in pool geometry (Buffington et al. 2002).

Time since Harvest - Channel response to streamside harvesting may be delayed given that instream wood can persist up to 100 years following clearcut harvesting in the absence of debris flows (Hassan et al. 2005a). Although no significant channel morphology changes were observed in the clearcut streams, wood was observed to be in an advanced state of decay especially in the older harvested streams (Chapter 5). This wood is more susceptible to physical fragmentation that could, in turn, result in future modifications to channel morphology as the wood deteriorates and with the occurrence of major channel defining flows. The susceptibility of channels to change may persist over the long term (>50 -100 years subsequent to harvesting) until future wood is recruited into the clearcut harvested streams. Future supplies of wood may also be reduced if successive harvest rotations are quite short, especially in the absence of episodic pulses of wood from major disturbances such as wildfires.

Streamside Clearcut Harvesting and Particles Smaller than 8 mm

One of the most common effects of forest management activities on streams is a decrease in bed particle sizes due to increased erosion and sediment delivery rates (MacDonald et al. 1991; Elliot 2000). Increases in erosion and sediment are a function of changes in bank erosion and instability rates, the frequency and occurrence of mass wasting to streams, exposure of mineral soils in cutblocks and the connectivity of cutblocks to streams, and the connectivity of roads to streams and road surface conditions.

In this study, the most notable difference in channel characteristics was the high number of particles smaller than 8 mm in the Harvest 70 disturbance category. However, it is difficult to ascribe this difference to harvesting alone, because the proportion of particle sizes smaller than 8 mm was the lowest in the Harvest 90 category, and the reference streams were intermediate in relation to the Harvest 70 and Harvest 90 categories. Factors related to bank erosion, mass wasting and surface erosion from cutblocks can be ruled out given limited or no observed evidence. Road surface conditions and connectivity of roads to streams is a likely cause of increased proportion of small particles observed in the Harvest 70 category. For example, there was evidence that an old road crossing situated directly above one of the study reaches (UNTRT1) had failed and had contributed a noticeable amount of sand and gravel sized particles to the stream. Also, roads associated with the study streams in the Harvest 70 category were likely built to a lower standard (e.g. poor drainage management with encroachment of roads in riparian areas) as compared to roads in the Harvest 90 category. The latter were built to a higher standard in concurrence with the Okanagan Timber Harvest Guidelines (BC Ministry of Forests 1992). Literature reviews have consistently highlighted unpaved roads as being the largest contributor of sediment to streams in areas unaltered by major landslides (Schnackenberg and MacDonald 1998; Elliot 2000; MacDonald and Stednick 2003; Gomi et al. 2005); therefore, the effects of roads on sediment delivery to these streams requires further research.

6.4.2 Channel Morphology in Relation to Wildfire and Stand Development Stages

Few channel morphology characteristics were found to have changed in relation to wildfire and the four stand development stages. Although limited research is available regarding the effects of fire on channel morphology (MacDonald and Stednick 2003), the main factors that can alter channel morphology subsequent to wildfire disturbance can be attributed to physical changes associated with increased runoff, sediment deposition or scouring and movement of instream wood (Minshall et al. 1997; Benda et al. 2003; Wondzell and King 2003) with the magnitude of effects being a function of severity of fire dictated by fire risk factors such as fuel loads, fuel moisture content, fuel continuity and topographic position (Dwire and Kauffman 2003). For example, high severity fires can create water repellent soils leading to increased overland flow and frequency of debris flows (Wondzell and King 2003).

Similar to the reasons already described above in Section 6.4.1, the direct effects of fire on channel morphology are a function of the frequency and occurrence of mass wasting events that reach streams (e.g. debris torrents, debris flows, landslides or snow avalanches), the inherent sensitivity of stream channels to disturbance, and changes in instream wood loads and mobility. Channel modifying events such as debris flows are rare in the study area due to a modest relief, decoupled hillslopes and highly infrequent landslides. Channels are also considered to be relatively resilient to changes in sediment, discharge or instream wood loads based on Montgomery and Buffington’s (1997) classification. Instream wood was also observed to be stable with no significant differences in the amount of wood transported between the stand development stages (refer Chapter 4); therefore, given these factors, significant changes in channel morphology are unlikely to be observed.

The number of particles smaller than 8 mm were significantly higher in the youngest stand development stage (Wildfire Category) as compared to the three remaining post-fire stand development stages. This finding is consistent with the literature since wildfires have been shown to have a strong influence on erosional processes (Wondzell and King 2003). Although direct sources for the increased proportion of fine sediment were not observed, the most likely source was "surface erosion from infiltration-excess overland flow," since this type of erosion has been found to be the dominant response after wildfire in the Interior region of the USA (Wondzell and King 2003) and was also observed to be a major surface erosion contributor immediately subsequent to wildfires that occurred in the south-central British Columbia in 2003 (Curran et al. 2006). Furthermore, lower proportions of particles smaller than 8 mm in the remaining three stand development stages are consistent with reduced surface erosion and overland flow as result of forest vegetation recovery.

6.4.3 Channel Morphology and Wood Relations

As has been found in previous studies (Bisson et al. 1987; Naiman et al. 2002; Hassan et al. 2005a), instream wood played a significant role in the formation of pools and was the primary influence on pool formation in the majority of disturbance categories and stand development stages. In addition, past studies (e.g. Murphy et al. 1986; Bilby and Ward 1991; Montgomery et al. 1995) have shown that reductions in wood associated with streamside clearcut harvesting can have significant effects on channel morphology. In my study wood-poor streams associated with forest harvesting were not observed and; therefore, channel morphology characteristics related to wood would be expected to be similar between disturbance categories and stand development stages. Even though streamside clearcut harvesting or wildfire was not shown to significantly influence channel morphology, wood still played an important role in pool formation; therefore, given the importance of pools to variety of aquatic species, maintaining adequate wood should still be an important consideration in riparian management in environments similar to my study sites.

6.5 CONCLUSION

Of the channel morphology variables only the finer bed particle sizes (< 8 mm) were altered as a result of streamside clearcut harvesting or wildfires as compared to streams flowing through unharvested older riparian forests. Similar channel morphology characteristics were observed in relation to stand development stage of adjacent riparian forests, with a higher amount of finer bed particle sizes observed in the wildfire category. Lack of significant changes in channel morphology subsequent to streamside clearcut harvesting or wildfire disturbances was most likely related to the inherent stability of the study streams, low frequency and occurrence of mass wasting events in the study area, low fluvial power of streams and the similar wood loads observed between the various disturbance categories and stand development stages. In all the study streams wood was found to play an important role in influencing pool formation; therefore, forest management practices that could limit supply of wood to streams over the long-term (>80 years) should be avoided.

Table 6.1. Description of channel unit and pool types (adapted from Kaufmann and Robison 1998).

Channel Unit Type		**Description**
Pools:		Still water, low velocity, smooth, glassy surface, deep compared to other parts of the channel.
	Plunge Pool (PP)	Pool at base of plunging cascade or falls
	Trench Pool (PT)	Pool-like trench in the center of the stream
	Lateral Scour Pool (PL)	Pool Scoured along a bank
	Backwater Pool (PB)	Pool separated from main flow off the side of the channel
	Impoundment Pool (PD)	Pool formed by impoundment above dam or constriction
Glide (GL)		Water moving slowly, with a smooth, unbroken surface. Low turbulence.
Riffle (RI)		Water moving, with small ripples, waves and eddies – waves not breaking surface tension not broken.
Rapid (RA)		Water movement rapid and turbulent, surface with intermittent white water with breaking waves.
Cascade (CA)		Water movement rapid and very turbulent over step channel bottom. Most of the water surface is broken in short, irregular plunges, mostly whitewater.
Falls (FA)		Free falling water over a vertical or near vertical drop into plunge, water turbulent and white over high falls.

Table 6.2. Comparison of average channel unit type, pool formation and pool forming elements in each of the four disturbance categories (standard deviation in brackets).

		Disturbance Category			
		Harvest 70	**Harvest 90**	**Old Forest**	**Wildfire**
Number of Sample Streams		5	7	8	6
Channel Unit Type (m/100 m)	Pools	19.8 (14.6)	14.6 (5.0)	15.5 (7.3)	18.8 (12.0)
	Glides	30.0 (14.9)	24.3 (14.2)	33.0 (14.2)	26.1 (16.3)
	Riffles	50.1 (14.8)	60.9 (17.3)	46.7 (16.1)	41.4 (26.0)
	Cascades	0.1 (0.3)	0.2 (0.5)	4.8 (3.1)	13.7 (27.3)
	Falls	0.0	0.0	0.0	0.0
Pool Formation (m/100 m)	Impoundment	9.7 (9.4)	3.1 (3.8)	7.4 (5.4)	10.3 (5.9)
	Lateral Scour	3.1 (3.2)	1.5 (1.6)	4.0 (5.3)	3.4 (4.5)
	Plunge	6.4 (5.3)	9.6 (5.0)	3.0 (2.8)	4.6 (4.8)
	Trench	0.6 (0.8)	0.4 (1.0)	1.1 (1.6)	0.5 (0.9)
Pool Forming Elements (%)	Boulders	20 (16)	8 (8)	33(33)	20 (29)
	Fluvial	16 (19)	6 (10)	21 (28)	7 (8)
	Small Wood	0 (0)	1 (4)	4 (6)	2 (4)
	Large Wood	64 (32)	85 (12)	42 (31)	70 (36)

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Table 6.3. Summary of mixed effect ANCOVA for pool formation, disturbance category and stream geometry covariates (stream gradient and bankfull width). Degrees of freedom for the model and error terms equal 11 and 14, respectively.

Pool Type Length (m/100 m)		**Disturbance Category (DC)**	**Stream Gradient (S)**	**Bankfull Width (Wb)**	**Interaction Terms DC x S**	**Interaction Terms DC x Wb**
Impoundment	F	2.52	2.35	3.03	0.71	2.32
	p-value	0.10	0.15	0.10	0.56	0.12
Lateral Scour	F	2.16	36.37	18.61	4.23	2.30
	p-value	0.14	**<0.01**	**<0.01**	**0.03**	0.12
Plunge	F	1.13	0.30	5.04	1.12	0.46
	p-value	0.37	0.60	**0.04**	0.37	0.71
Trench	F	0.17	0.51	0.46	0.27	0.68
	p-value	0.92	0.49	0.51	0.84	0.58

Table 6.4. Summary of ANCOVA for pool type as response variable and disturbance category and wood quantity as covariates (i.e. wood abundance and volume). Degrees of freedom for the model and error terms equal 11 and 14, respectively.

Pool Type Length (m/100 m)		Disturbance Category (DC)	Wood Abundance (WA)	Wood Volume (WV)	Interaction Terms	
					DC x WA	DC x WV
Impoundment	F	1.05	3.41	0.49	2.89	1.52
	p-value	0.40	0.09	0.50	0.07	0.25
Lateral Scour	F	1.06	0.02	0.04	2.02	1.26
	p-value	0.40	0.88	0.84	0.16	0.33
Plunge	F	2.33	1.01	0.06	1.08	1.88
	p-value	0.12	0.33	0.81	0.39	0.18
Trench	F	0.19	0.46	0.14	0.24	0.21
	p-value	0.90	0.51	0.72	0.87	0.89

Table 6.5. Contingency table of the frequency of particles smaller than 8 mm in each of the four disturbance categories. The frequency of particles smaller than 8 mm and the four disturbance categories were dependent based on the chi-square test statistic for independence (X^2 = 113.43, p < 0.001).

Particle Size	Disturbance Category			
	Old Forest	Wildfire	Harvest 90	Harvest 70
Particles < 8 mm	160	194	94	184
Particles ≥ 8 mm	720	466	677	366

Table 6.6. ANCOVA comparison of various channel morphology characteristics between the four disturbance categories. Degrees of freedom for the model and error terms equal 11 and 14, respectively.

					Interaction Terms	
Response Variable		**Disturbance Category**	**Stream Gradient**	**Bankfull Width**	**Disturbance Category x Gradient**	**Disturbance Category x Bankfull Width**
Total pool length (m/100 m)	F	2.14	12.69	17.60	0.45	1.75
	p-value	0.141	**0.003**	**<0.001**	0.722	0.203
Pools formed by wood (m/100 m)	F	1.82	1.147	2.506	0.318	1.57
	p-value	0.191	0.302	0.136	0.812	0.240
Pool Spacing (Wb / pool)*	F	0.121	0.893	0.698	0.375	0.226
	p-value	0.946	0.361	0.417	0.772	0.877
Pool / Riffle Ratio (m / m)	F	1.73	19.71	9.58	1.48	1.08
	p-value	0.206	**<0.001**	**<0.008**	0.263	0.390
Banfull Width Coefficient of Variation (%)	F	1.73	0.333	2.63	2.94	1.05
	p-value	0.206	0.573	0.127	0.070	0.400
Average Residual Pool Depth (m)	F	0.692	0.547	0.342	0.899	1.43
	p-value	0.572	0.472	0.568	0.466	0.275
Maximum Pool depth* (m)	F	0.906	0.964	0.355	1.395	3.53
	p-value	0.463	0.343	0.561	0.286	**0.043**
Residual Pool Area (m^2/100 m)	F	1.95	10.74	8.416	1.69	3.184
	p-value	0.169	**<0.001**	**<0.001**	0.215	0.057
Total Pool Volume (m^3/100 m)*	F	0.534	5.92	0.814	0.397	0.734
	p-value	0.667	**0.029**	0.382	0.757	0.549

*Response variable log transformed.

Table 6.7. Average number of deep pools (residual pools > 30 cm) per 100 m in relation to the four disturbance categories.

Disturbance Category	n	Deep Pools (#/100 m)	
		Average Number	Std. Dev.
Harvest 90	7	0.9	0.9
Harvest 70	5	1.4	2.1
Old Forest	8	0.4	0.7
Wildfire	6	0.8	0.4

Table 6.8. Comparison of average channel unit type, pool formation and pool forming elements in the four stand development stages (standard deviation in brackets).

		Stand Development Stage			
		0-50	>50 - 100	>100 - 150	>150 - 200
Number of Sample streams		6	8	6	6
Channel Unit Type (m/100 m)	Pools	18.8 (12.0)	11.7 (4.6)	17.0 (6.1)	15.0 (7.3)
	Glides	26.1 (16.3)	27.8 (12.4)	24.4 (17.8)	29.5 (11.8)
	Riffles	41.4 (26.0)	58.2 (11.9)	56.0(18.8)	50.1 (16.2)
	Cascades	13.7 (27.3)	2.2 (2.5)	2.6 (3.0)	5.4 (2.8)
	Falls	0.0	0.1 (0.2)	0.0	0.0
Pool Formation (m/100 m)	Impoundment	10.3 (5.9)	3.8 (4.6)	6.9 (6.3)	8.4 (6.0)
	Lateral Scour	3.4 (4.5)	3.6 (4.3)	2.7 (4.6)	3.3 (4.8)
	Plunge	4.6 (4.8)	3.7 (2.6)	6.5 (3.3)	2.8 (3.3)
	Trench	0.6 (0.9)	0.7 (1.1)	1.2 (1.9)	0.4 (0.7)
Pool Forming Elements (%)	Boulders	20 (29)	7 (17)	42 (41)	35 (36)
	Fluvial	7 (8)	12 (12)	19 (32)	13 (15)
	Small Wood	2 (4)	3 (7)	4 (7)	1 (3)
	Large Wood	70 (36)	79 (22)	34 (35)	51 (31)

Table 6.9. Summary of mixed effect ANCOVA for the pool formation, four stand development stages and stream geometry covariates (stream gradient and bankfull width). Degrees of freedom for the model and error terms equal 11 and 14, respectively.

Pool Type Length (m / 100 m)		**Stand Development Stage (SDS)**	**Stream Gradient (S)**	**Bankfull Width (Wb)**	**Interaction Terms**	
					SDS x S	**SDS x Wb**
Impoundment	F	2.10	0.520	0.065	1.170	2.92
	p-value	0.145	0.483	0.803	0.356	0.071
Lateral Scour	F	0.305	7.22	3.39	0.399	0.646
	p-value	0.821	**0.018**	0.087	0.756	0.598
Plunge	F	1.012	0.008	2.327	0.894	1.097
	p-value	0.417	0.931	0.149	0.468	0.383
Trench	F	1.033	1.904	0.244	0.727	0.108
	p-value	0.408	0.189	0.629	0.552	0.954

Table 6.10. Summary of ANCOVA for pool formation, four stand development stages and wood quantity covariates (i.e. wood abundance and volume). Degrees of freedom for the model and error terms equal 11 and 14, respectively.

Pool Type		**Stand Development Stage (SDS)**	**Wood Abundance (WA)**	**Wood Volume (WV)**	**Interaction Terms**	
					SDS x WA	**SDS x WV**
Impoundment	F	0.557	0.168	0.010	1.020	0.122
	p-value	0.652	0.689	0.922	0.414	0.946
Lateral Scour	F	0.8425	1.5908	0.2555	0.6026	0.4430
	p-value	0.4931	0.2278	0.6211	0.6240	0.7260
Plunge	F	0.9556	0.5134	1.3728	1.6118	1.1876
	p-value	0.4407	0.4854	0.2609	0.2314	0.3501
Trench	F	0.0543	0.5313	0.0898	0.1938	0.0759
	p-value	0.9827	0.4781	0.7688	0.8989	0.9720

Table 6.11. Contingency table of the frequency of particles smaller than 8 mm in each of the four stand development stages. The frequency of particles smaller than 8 mm and the four stand development stages were dependent based on the chi-square test statistic for independence (X^2 = 84.05, p < 0.001).

Particle Size	**Stand Development Stage (years)**			
	0-50 year	**>50-100**	**>100-150**	**>150-200**
Particles < 8 mm	194	126	73	125
Particles ≥ 8 mm	466	754	587	535

Table 6.12. ANCOVA comparison of various channel morphology characteristics in relation to the four stand development stages. Degrees of freedom for the model and error terms equal 11 and 14, respectively.

					Interaction Terms	
Response Variable		**Stand Development Stage**	**Stream Gradient**	**Bankfull Width**	**Stand Development Stage x Gradient**	**Stand Development Stage x Bankfull Width**
Total pool length (m/100 m)*	F	1.58	6.43	4.58	0.900	1.60
	p-value	0.240	**0.024**	**0.050**	0.466	0.233
Pools formed by LWD (m/100 m)	F	2.5486	0.1790	3.7641	1.9817	4.1919
	p-value	0.0977	0.6787	0.0728	0.1631	**0.0259**
Pool Spacing (Wb/pool)	F	0.233	0.009	0.920	0.474	0.092
	p-value	0.872	0. 926	0.355	0.706	0.963
Pool / Riffle Ratio (m/m)*	F	0.638	23.84	4.73	2.32	1.88
	p-value	0.603	**<0.001**	**0.047**	0.119	0.179
Banfull Width Coefficient of Variation (%)	F	1.03	0.76	6.26	1.29	2.04
	p-value	0.410	0.395	**0.025**	0.317	0.154
Average Residual Pool Depth (m)*	F	0.771	0.002	2.86	1.14	0.880
	p-value	0.530	0.968	0.113	0.367	0.475
Maximum Pool depth* (m/100 m)	F	0.266	0.001	0.438	0.974	0.346
	p-value	0.849	0.980	0.519	0.433	0.793
Residual Pool Area (m^2/100 m)	F	0.549	2.534	0.400	2.28	0.655
	p-value	0.657	0.133	0.537	0.124	0.593
Total Pool Volume (m^3/100 m)*	F	0.687	0.271	0.205	1.437	0.246
	p-value	0.575	0.611	0.657	0.274	0.863

*Response variable log transformed.

Table 6.13. Average number of deep pools (residual pools > 30 cm) per 100 m in relation to the four stand development stages.

Stand Development Stages	n	Deep Pools (#/100 m)	
		Average Number	Std. Dev.
0-50	6	0.8	0.4
>50-100	8	1.5	1.2
>100-150	6	0.7	0.8
>150-200	6	0.5	0.8

Table 6.14. Multiple linear regression results showing the relative influence of instream wood and channel characteristics on various habitat variables. Analysis does not include streams that experienced streamside clearcut harvesting (n = 26).

Response Variable	Coeff.	Explanatory Variable	Standard Error	Regressor p-value	r^2	Adj. r^2	p-value
Total pool length (m/100 m)	34.98	constant	4.54	<0.001	**0.47**	**0.42**	**<0.001**
	-0.94	gradient (%)	0.43	0.039			
	-5.32	bankfull width (m)	1.39	<0.001			
Pools formed by wood (m/100 m)	-25.65	constant	13.22	0.06	**0.49**	**0.45**	**<0.001**
	-6.01	bankfull width (m)	1.83	0.003			
	13.61	Number wood pieces per 100 m (Log Transformed)	3.33	<0.001			
Pool Spacing (Wb/pool)		No Significant Variables					
Pool / Riffle Ratio (m/m)	2.45	constant	0.79	0.005	**0.53**	**0.47**	**<0.001**
	-0.17	gradient (%)	0.05	0.003			
	-0.72	bankfull width (m)	0.22	0.003			
	4.31	bankfull depth (m)	1.98	0.040			
Bankfull Width Coefficient of Variation (%)	45.14	constant	7.61	<0.001	0.21	0.17 **Low r^2**	0.020
	-6.77	bankfull width (m)	2.72	0.020			
Average Residual Pool Depth (m)	0.07	constant	0.02	0.002	0.33	0.30 **Low r^2**	0.002
	0.02	bankfull width (m)	0.01	0.002			
Maximum Pool depth (m)	0.20	constant	0.07	0.005	0.19	0.15 **Low r^2**	0.027
	0.06	bankfull width (m)	0.02	0.027			
Longitudinal Residual Pool Area (m^2/100 m)	5.98	constant	0.92	<0.001	0.15	0.11 **Low r^2**	0.048
	-0.15	D (cm)	0.07	0.048			
Total Pool Volume (m^3/100 m)		No Significant Variables					

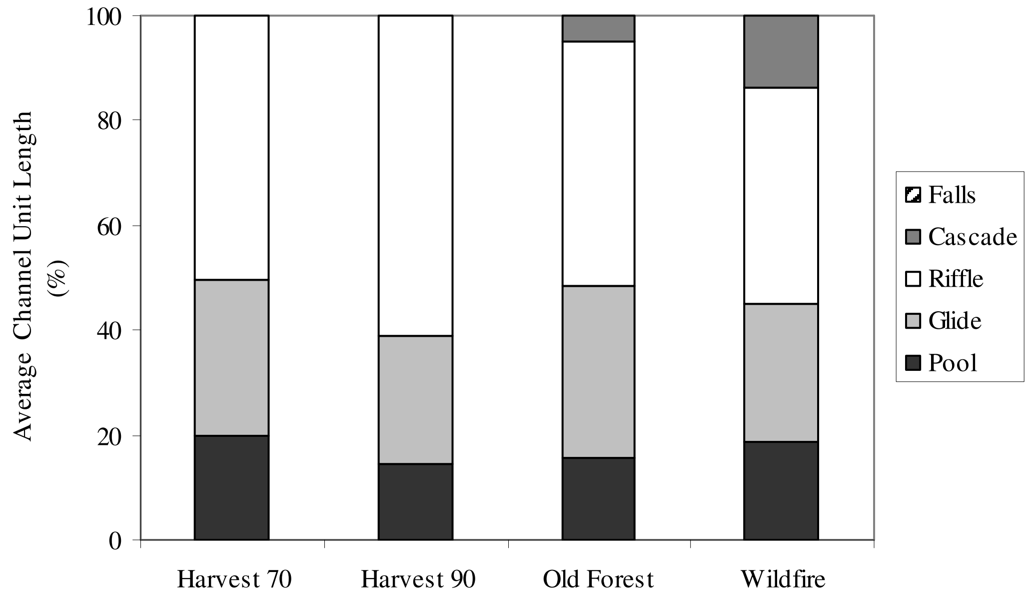


Figure 6.1. Average channel unit length in relation to the four disturbance categories.

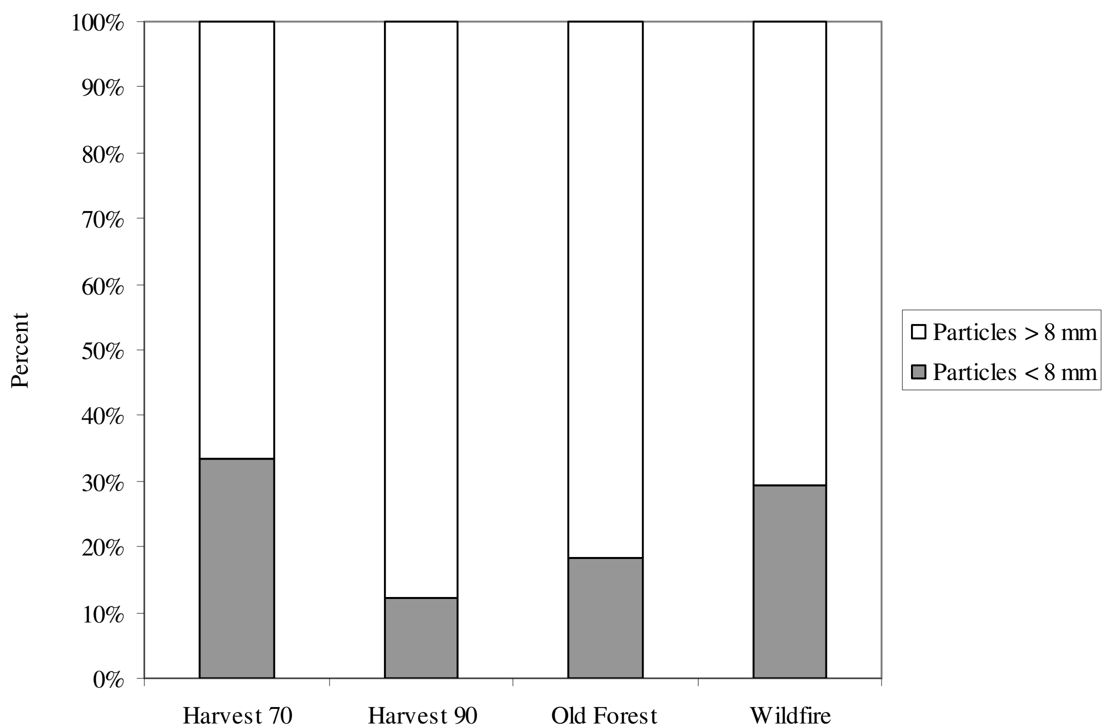


Figure 6.2. The percent of particles smaller than 8 mm in relation to the four disturbance categories.

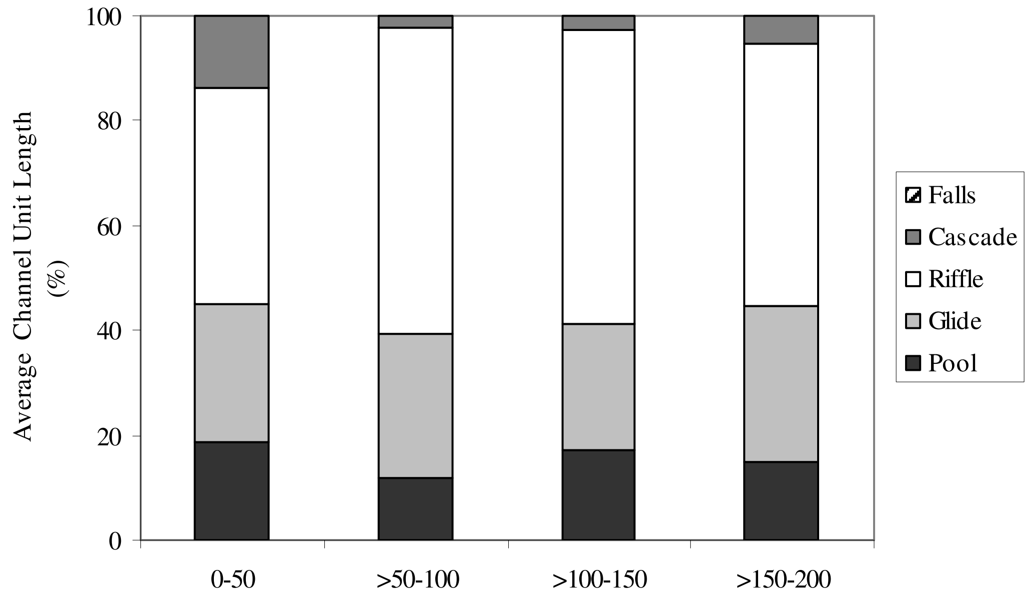


Figure 6.3. Average channel unit length in relation to the four stand development stages.

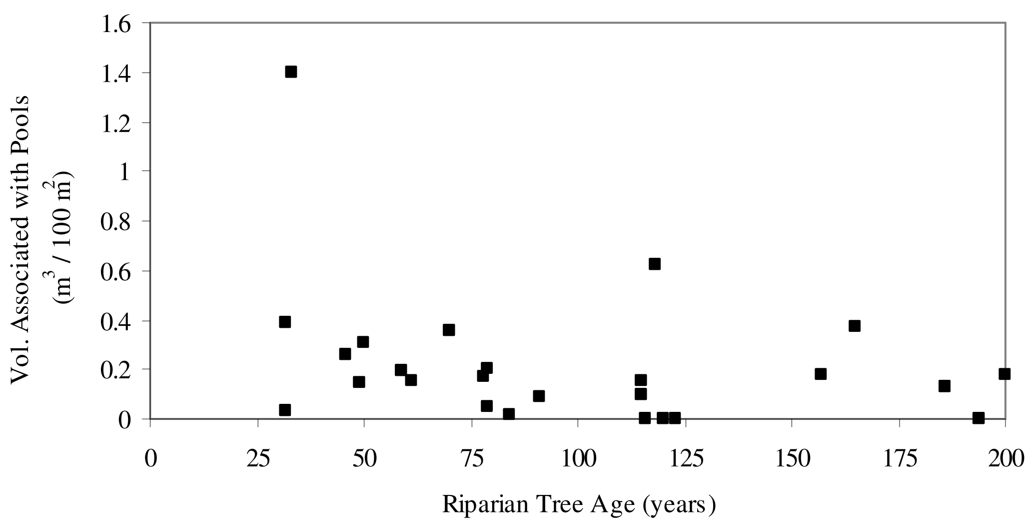


Figure 6.4. Wood volume associated with pools in relation to the time since the last major wildfire disturbance.

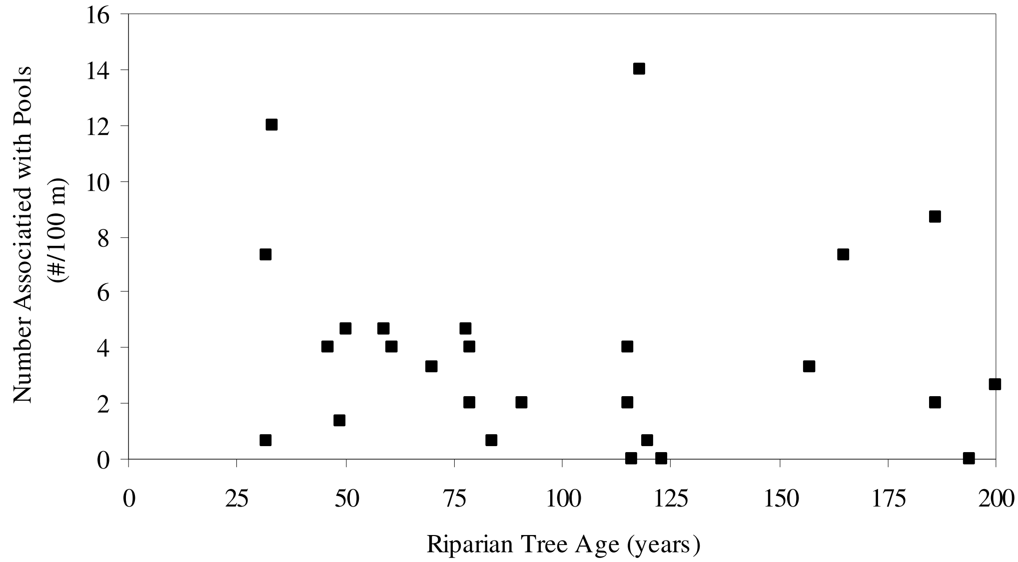


Figure 6.5. Wood number associated with pools in relation to the time since the last major wildfire disturbance.

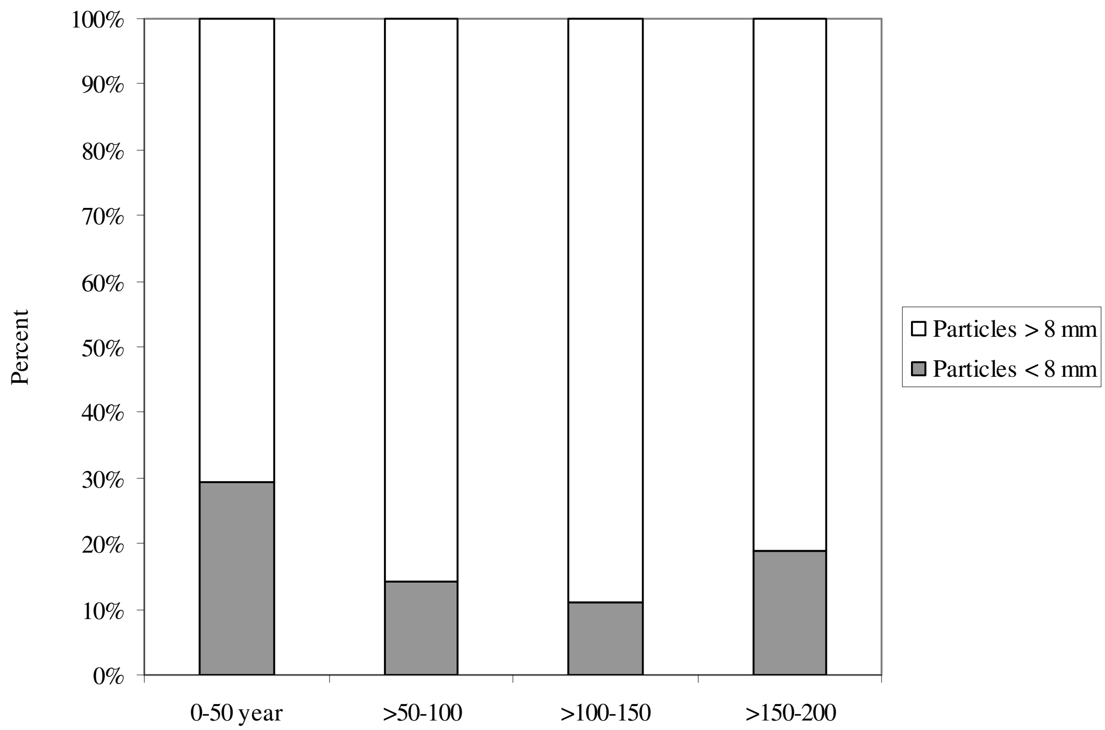


Figure 6.6. The percent of particles smaller than 8 mm in relation to the four stand development stages.

CHAPTER 7

REACH SCALE SPATIAL DISTRIBUTION OF INSTREAM WOOD

This chapter evaluates the spatial distribution of wood in relation to disturbances (wildfire or streamside clearcut logging) and assesses sample length and sample size required to estimate wood abundance and volume. It incorporates the wood quantity measurements, disturbance categories and stand development stages already discussed in Chapter 4 and 5.

7.1 INTRODUCTION

Understanding the spatial distribution of instream wood is important for several reasons. First, understanding trends and spatial patterns from an ecological perspective can improve understanding of underlying processes that formed these patterns (Levin 1992). Second, characterization and quantification of patterns and trends can be a precursor to ensuring appropriate application of sampling methodologies (e.g. sample size and length) and statistical tests (Robison 1997; Trainor and Church 2003; Young et al. 2006). Third, examination of trends and patterns in wood distribution can provide valuable insight into the effects of disturbances and/or restoration activities (Wing et al. 1999; Keim et al. 2000; Kraft and Warren 2003).

In one-dimensional transect data, three basic spatial patterns can occur: random, clumped (aggregated) or uniform (Fortin and Dale 2005). Identification of the spatial pattern of data has important implications in sample design and analysis (Fortin and Dale 2005).

For example identification of a random pattern can reduce the number or length of reach segments required to determine wood loads at a desired level of precision (Lutes 2002). Reduced sample lengths translate into reduced sample effort (Lutes 2002). Also, randomness is one of the key assumptions in determining if parametric, univariate statistics can be applied. If the assumptions of stationarity, randomness and fixed distribution are reasonable, then a univariate model can be applied. However, if the randomness assumption is not valid then a different model needs to be used, such as a time series model or non-linear model (with space or time as a variable).

Until recently, the majority of the instream wood research has been primarily devoted to understanding the geomorphic role that wood plays in stream channels with only a few studies (e.g. Hogan 1986; Robison and Beschta 1990; Nakamura and Swanson 1993; Richmond and Fausch 1995; Hogan et al. 1998) providing qualitative descriptions of the spatial distribution of instream wood (Wing et al. 1999). Recent exceptions where quantitative analyses have been conducted include research by Wing et al. (1999), Keim et al. (2000), Kraft and Warren (2003) and Young et al. (2006). Wing et al. (1999) and Keim et al. (2000) examined the distribution of wood in a single study reach from high-resolution spatial data sets using geostatistical tools (i.e. nearest neighbour analysis and semi-variograms) to assess the aggregation of placed wood from restoration activities in a Oregon Coast Range stream (channel with ~ 6-7 m). Kraft and Warren (2003) examined the linear pattern of individual pieces of wood and debris jams in eight streams (channel widths ~ 5-13 m) of the Adirondack Mountains subsequent to extensive wood deposition from ice storms. Kraft and Warren (2003) utilized a one dimensional nearest neighbour approach. Young et al. (2006) examined the spatial distribution of wood in > 1000 m sample segments to determine whether spatial correlation (using correlograms) was present between consecutive 50 m stream reaches within 13 streams of western Montana (channel widths ~ 4.5 to 7.8 m).

Although the above mentioned studies have provided important insights into the spatial distribution of wood, none of these studies explored the spatial distribution in relation to disturbances such as wildfire or streamside clearcut harvesting. Also, none of these studies focused on small streams (< 5 m in width), which are often directly affected by forest harvesting or stand replacing wildfires. Consequences of the modification or redistribution of wood subsequent to disturbances can lead to reduced storage of bedload behind wood, shallower pool depths, reduced habitat complexity and habitat stability (Hogan 1986; Ralph et al. 1994).

Another important outcome from determination of the spatial distribution of instream wood is evaluation of the reach length required to estimate wood loads within a given level of certainty. Past research (e.g. Ralph et al. 1994; Benda et al. 2003; Young et al. 2006) has argued that several studies (Leopold et al. 1964; Fitzpatrick et al. 1998; Kaufmann et al. 1999; as presented by Young et al. 2006) have used insufficient sample lengths to characterize instream wood loads. Several of these studies have assumed that sample lengths of 20-40 multiples of bankfull width are sufficient to characterize wood abundance and volume within a stream (Young et al. 2006). This assumption appears to be based on channel morphology studies that have demonstrated that sample lengths at this scale are adequate for characterizing channel morphology (e.g. Platts 1983; Simonson et al. 1994; Robison 1997). Based on an analysis of entire stream networks with sample lengths exceeding a kilometer, Young et al. (2006) argued that this assumption cannot be extended to determination of mean wood volumes and abundance if the objective is to measure mean wood volumes and abundance with a relatively high level of certainty (i.e. mean values within 25% of the true mean).

The objectives of this chapter were (1) to statistically characterize the spatial distribution of instream wood (volume and abundance) in several small streams, (2) to determine whether the spatial distribution of wood was altered as result of streamside clearcut harvesting and wildfire disturbance, (3) to assess whether the pattern varied temporally as a result of riparian stand development, and (4) to determine the length of stream and sample size required to estimate and compare wood loads to certain level of certainty.

This chapter addressed the following primary hypotheses:

1. Wood loads (volume and abundance) within first and second order streams of south-central British Columbia (bankfull widths < 5 m) are randomly distributed and contain no trend (monotonic) in wood volume or abundance in a downstream direction.
2. The spatial distribution of wood loads (volume and abundance) will be altered in small streams disturbed by streamside clearcut harvesting or wildfires (10-50 years ago) as compared to old, unharvested forests. Subsequent to streamside clearcut harvesting or wildfires it is hypothesized that wood pieces would be redistributed and not randomly distributed due to the interplay of

reduced lateral recruitment of wood subsequent to streamside disturbances, the decomposition and fragmentation of preexisting instream wood and increased transport of decomposed and fragmented pieces into debris accumulations.

3. The spatial distribution of wood loads (volume and abundance) in small streams will change in relation to stand development stage of adjacent riparian forests. Similar to #2 above, the hypothesized mechanism for change in wood distribution in relation to stand development stage is related to temporal changes in the interplay between lateral recruitment processes, instream decomposition and fragmentation of wood and wood transport.
4. A reach length of 150 m (30 to 50 times bankfull width) is adequate to characterize wood volume and abundance in small streams of south-central British Columbia within 25% of the mean.

7.2 METHODS

7.2.1 Spatial Arrangement and Distribution

To assess the spatial distribution of wood, the distance to each wood piece from the lower end of the reach was measured along the 38, 150 m long study reaches using a string box tape dragged along the thalweg. All instream wood pieces that were within or above the bankfull margins of the stream channel and were at least 10 cm in diameter and no smaller than 1 m in length were measured. The small end diameter down to 10 cm and large end diameter of each wood piece situated within or above the vertical limits of channel bankfull width were recorded. The volume of each wood piece situated within or above the vertical limits of channel bankfull width was calculated as a cylinder (Hogan 1987; Robison and Beschta 1990):

$$V = L \bullet \pi \bullet \frac{\bar{d}^2}{4} \tag{7.1}$$

where L = piece length (m) and $\bar{d}$ = mean diameter (m).

Wood volume and abundance were then grouped into consecutive intervals using a 3 m subsection length, 5 m subsection length and 10 m subsection length. Three interval lengths were used since detection of spatial patterns can change with scale (Fortin and Dale 2005). These three intervals provided sufficient sample sizes for statistical analysis and ranged in scale from one channel width to four to seven channel widths. The distance along the thalweg between consecutive wood pieces was also calculated and was evaluated for pattern and trend in each study stream. Wood pieces that were in close proximity and overlapped were designated as having zero distance between pieces.

Two nonparametric tests were used to test the first hypothesis. The runs test was used to assess departures in randomness (Zar 1999), while the Mann-Kendall test (Mann 1945; Kendall 1975) was used to assess the data sequences for monotonic trend. The advantage of using these two nonparametric tests is that they are less restrictive in required assumptions (e.g. underlying statistical distribution) than other parametric tests (Zar 1999). Systat (Version 12) statistical software was used to conduct all runs tests and Mann-Kendall tests using an alpha value of 0.05.

Nonparametric tests for independence were used to evaluate the second and third hypothesizes (Table 7.1 and 7.2), specifically as to whether the existence of random/non-random distribution and presence/absence of monotonic trend varies among disturbance categories or stand development stages to explore the relation between the frequencies of the results from the runs tests (random versus nonrandom) or Mann-Kendall tests (no trend versus significant trend) and the four disturbance categories or stand development stages (Table 7.1 and 7.2). Exact nonparametric inference using asymptotic (i.e. p-values based on large sample assumption) and Monte Carlo methods were used in all the tests for independence due to sparse cell frequencies and to ensure reliable inferences. StatXact (Version 7.0) was used for all tests for independence using an alpha value of 0.05.

The spatial distribution of wood pieces was further assessed for randomness by comparing the observed frequency distribution of wood abundance in each of the three consecutive subsection intervals to a Poisson probability distribution. A Poisson distribution can be used to indicate the independence between the number of events (Young and Young 1998). A Poissonness Plot (Hoaglin 1980; Friendly 2000) and the Kolmogorov-Smirnov one sample test were used to judge goodness-of-fit. The Poissonness plot is analogous to the quantile-quantile probability plot used to assess whether or not observed data come from a certain continuous distribution (e.g. normal distribution) (Hoaglin 1980). The distribution of the distances along the thalweg between consecutive wood pieces was also compared to an exponential distribution under the assumption that the distance between successive, randomly spaced events follows an exponential distribution (Young and Young 1998). This assumption is based on the unique relationship between a Poisson and exponential distribution, in that the space between occurrences of random events (Poisson process) has an exponential distribution (Young and Young 1998). Goodness-of-fit of the exponential distribution was assessed using the Kolmogorov-Smirnov one sample test. Kolmogorov-Smirnov test statistics were calculated using Easyfit (Version 3.3) using an alpha value of 0.05.

7.2.2 Sample Length and Size Calculations

To determine the reach length required in individual study streams to estimate mean wood volume and abundance to certain level of uncertainty (i.e. accuracy) a sample size estimator (Cochran 1977; Eckblad 1991) was used. Sample size estimates were calculated from sample means and variances for each of the three interval lengths (3 m segment, 5 m segment and 10 m segment) generated from the wood volume and abundance data collected in all 38 study streams. Sample sizes or the number of subsection intervals required for each study stream were calculated using the following formula:

$$n = \frac{(t)^2 S^2}{(r\overline{X})^2}$$

where;

t = t-value based on theorectical population mean,

S^2 = sample variance,

r = relative error or uncertainty in the estimated population mean, and

$\overline{X}$=sample mean

From this formula total required reach lengths for a given level of uncertainty were calculated by multiplying the estimated sample size (n) by the given subsection interval length (3 m segment, 5 m segment and 10 m segment).

A post-hoc power analysis was used to calculate the number of 150 m study reaches that would be required to minimize the probability of making a type II error (incorrectly concluding that there is no effect when there really is) given a certain level of power (e.g. 80%) in comparison of instream wood loads (volume and abundance) between streamside clearcut harvested areas versus older, relatively undisturbed forested stands. It is important to highlight that the post-hoc power analysis was not an analysis of the power of the multiple comparisons (One-way ANOVA tests) used in this study that failed to reject the null hypothesis for mean differences in wood volumes or abundance between the different disturbance categories or stand development stages (refer to Chapter 4 and 5) since this approach is controversial and has been shown to be "fundamentally flawed" (Hoenig and Heisey 2001). Instead, the intent of this power analysis was to highlight the limits of statistical inference that can be made from similar research or monitoring activities that may be conducted in the future that are designed to quantify potential changes in instream wood loads associated with streamside clearcut harvesting as compared to older, undisturbed forest stand conditions. Based on this intent, only data from the streamside clearcut harvested streams (Harvest 70 category, n = 5) and the older, undisturbed forest stand conditions (Old Forest category, n = 8) assessed in Chapter 5 were used in the power analysis with the estimated power being based upon comparison of two independent groups (i.e. t-test). In the power analysis four different raw effect sizes (i.e. 20%, 40%, 60% and 80% difference between mean wood volume or abundance) were used to determine sample size requirements given a specified level of power. Power analyses were also based on the observed pooled standard deviations generated from the comparison of the original wood volume and abundance datasets and an alpha of 0.05. The statistical software JMP developed by SAS Institute Inc. was utilized in all power/sample size calculations.

7.3 RESULTS

7.3.1 Spatial Distribution Overview

Pattern - Of the 114 runs tests performed on wood volume, only 6 (5%) of the tests indicated a non-random pattern, with 4 of these tests occurring at the 3 m segment scale (Table 7.3). Similarly, of the 114 tests performed on wood abundance, only 3 (3%) of the tests indicated a non-random pattern, with all of these tests occurring at the 3 m segment scale (Table 7.4). None of the study streams had more than one segment interval showing a non-random pattern for both wood volume and abundance. The distance between wood pieces was also observed to be randomly distributed in the majority of study streams, with 7 (18%) out of 38 having a non-random pattern (Table 7.5). A graphical example of the spatial distribution of wood volume and abundance for streams observed to have a random pattern are shown in Figure 7.1 and 7.2.

Trend - Of the 114 Mann-Kendall tests performed on wood volume, 15 (13%) of the tests indicated a significant trend, and of the 114 tests performed on wood abundance, 16 (14%) of the tests indicated a significant trend (Table 7.6). Also, based upon visual inspection of scatter plots and the runs test results no adjustments for serial correlation were required. Three of the study streams showed a consistent trend in at least three of the segment intervals (PASAYTEN1, ELLIS and PEACH1). The trend in the distance between wood pieces was only significant in 3 (8%) out of 38 of the study streams (Table 7.5). The study streams with significant trend in wood volume and abundance in the 3 m or 5 m subsection intervals had positive trend in an upstream direction. Positive trend was also observed in the three study reaches that showed a significant trend in the distance between wood pieces. No consistent trend was observed for wood volume or abundance in the 10 m subsection interval with 3 to 4 of the study reaches showing a positive trend and 5 to 6 showing a negative trend pattern in relation to wood volume or abundance. A graphical example of the spatial distribution of wood volume and abundance for streams observed to have a significant trend pattern are shown in Figure 7.3 and 7.4.

7.3.2 Pattern and Trend in Relation to Disturbance Category

Tables 7.8 to 7.13 show the frequency of pattern and trend in wood volume, abundance or distance between wood pieces in relation to each of the four disturbance categories. In all cases, none of the tests for independence was significant, indicating that the observed spatial distribution of wood was independent of the four disturbance categories (Table 7.14).

7.3.3 Pattern and Trend in Relation to Stand Development Stage

The following contingency tables (Tables 7.15 to 7.20) show the frequency of pattern and trend in wood volume, abundance or distance between wood pieces in relation to each of the stand development stages. In all cases except one, the tests for independence were not significant, indicating that the observed spatial distribution of wood was independent of the stand development stage (Table 7.21). For the one exception (Table 7.18), trend in wood abundance was not independent of stand development stage, with the 51-100 year stand development stage having a higher proportion of study streams with significant trend compared to the remaining three stand development stages in the 10 m subsection interval.

7.3.4 Frequency Distribution of Wood Abundance and the Distance Between Pieces

Wood abundance in each of the three subsection intervals followed a Poisson distribution in all 38 study streams based upon the Kolmogorov-Smirnov goodness-of-fit test; however, at the smallest subsection interval (3 m segment) departures from a straight line fit were observed in the Poissonness plots as compared to the larger subsection intervals (5 m segment and 10 m segment) (Figure 7.5 and 7.6). Furthermore, the distance between wood pieces only followed an exponential distribution in 14 of the 38 study streams (Figure 7.7). Study streams that did not fit an exponential distribution (Figure 7.8) were characterized by greater number of pieces in the smallest spacing class (0 to 0.5 m), a moderate number in the intermediate spacing (1 – 5 m) and more pieces in the larger spacing classes (>5 m) than would have been expected given an exponential distribution.

This finding also indicates that at small spatial scales (<3 m) there is a departure from randomness, with wood being more clustered as opposed to evenly distributed through the study streams.

7.3.5 Reach Length Estimation and Power Analysis

The average length of stream required to estimate wood volume and abundance with a given level of uncertainty for each of the three subsection intervals is shown in Figures 7.9 and 7.10. Average reach lengths and the corresponding 95% confidence intervals for the 3 m subsection interval are also provided in Figure 7.11 and 7.12. Sample lengths of 150 m (30 to 50 times bankfull width) were found to estimate wood volume within 40% of the mean and wood abundance within 30% of the mean. For an uncertainty level within 25% of the mean, reach lengths of 420 m would be required for wood volume and 210 m required for wood abundance. Therefore, the 150 m sample reach length was not adequate to characterize wood volume and abundance within 25% of the mean. Based on typical stream widths (3 m to 5 m) observed in this study a 420 m sample length corresponds to 84 to 140 bankfull widths and 210 m corresponds to 42 to 70 bankfull widths. This equates to individual reach lengths that are approximately 1.4 to 2.5 times greater than were utilized in this study.

The power analysis curves in Figure 7.13 and 7.14 show the number of 150 m study streams required to detect differences in mean wood volume and abundance between streams flowing through the older clearcut harvested as compared to undisturbed, older forested areas. Based on these figures, 30-50 study streams would be required to obtain an 80% chance of detecting differences of 60 to 80% for wood volume. For wood abundance, 15-20 study streams would be required to detect similar differences. Sample sizes exceeding 100 study streams would be required to detect a 40% difference in mean wood volume and approximately 50 study streams would be required to detect similar differences in mean wood abundance. Due to the amount of variation between sample streams, substantially larger sample sizes (> 300) would be required to detect relatively small differences (20% difference) in mean wood volume or abundance.

7.4 DISCUSSION

7.4.1 Overall Pattern and Trend

For the most part and especially at larger spatial distances (> 3 m), wood volume and abundance were randomly distributed and contained no trend within the study streams. This random pattern likely reflects the "dispersed-source control pattern" that is described by Swanson (2003). Basically, wood inputs stay where they have fallen and entered the stream (Swanson 2003). This observed random distribution can be further explained by the fact that small streams tend to be narrow in width relative to wood piece length, with the majority of wood pieces being dominated by local, lateral recruitment processes from adjacent riparian areas due to episodic or chronic mortality (e.g. suppression mortality) of the riparian forest stand. This observed random pattern is consistent with other studies conducted in first to third order streams (e.g. Bisson et al. 1987, Robison and Beschta 1990, Richmond and Fausch 1995, May and Gresswell 2003). In comparison, larger, wider streams have higher transport capacities due to higher discharges, and wood piece lengths are typically smaller than channel widths. Therefore, in wider streams wood tends to accumulate in jams and has a more clumped pattern (Nakamura and Swanson 1993; Richmond and Fausch 1995; Abbe and Montgomery 1996).

Although the spatial arrangement of wood reflects the "dispersed-source control pattern" described by Swanson (2003), departures from randomness at the smaller spatial scales (<3 m) were observed. As described by Scheidt (2006) these departures from randomness are likely related to clumping of wood associated with multiple trees falling in the same locations, one tree knocking over others, localized wind bursts, localized wood transport of smaller decayed pieces, localized disease and/or localized undercut banks. These departures from randomness further highlight the importance of considering the interaction between individual trees when estimating the spatial arrangement of wood within small streams as described by Gregory et al. (2003) and Scheidt (2006).

An important exception that can have a major effect on the spatial pattern of wood in small streams is the occurrence of mass wasting events such as debris flows (Gomi et al. 2001; May and Gresswell 2003; Benda et al. 2005). Debris flows and other mass wasting events have been shown to contribute large amounts of wood to steep headwater streams (Gomi et al. 2001; May and Gresswell 2003). In steep headwater streams, mass wasting events scour wood from transport zones and deposit wood in run-out zones (e.g. tributary junctions or gradient breaks) creating a more clumped distribution of wood in headwater areas (Gomi et al. 2001). This distribution is common in steep headwater streams of the Pacific Northwest (Benda et al. 2005) but mass wasting events such as debris flows are uncommon in the low gradient streams situated in the Okanagan Highlands and

Thompson Plateau; therefore, a more random pattern of wood is expected. Forest harvesting on steep hillslopes can increase the frequency of mass wasting and can lead to the depletion of future wood contributions to streams (Gomi et al. 2001; May and Gresswell 2003). In regards to the streams in this study, harvesting on upslope areas was not associated with the maintenance of wood contributions since the majority of wood contribution was observed to come from adjacent riparian areas.

7.4.2 Pattern and Trend in Relation to Disturbances or Stand Development Stage

Streamside Clearcut Harvesting - It was hypothesized that subsequent to streamside clearcut harvesting, wood pieces would be redistributed and would not be randomly distributed due to the interplay of reduced lateral recruitment of wood subsequent to streamside logging, decomposition and fragmentation of preexisting instream wood and increased transport of decomposed and fragmented pieces into debris accumulations. However, this expected non-random distribution was not observed and highlights the overall stability of wood in the study streams even 20-30 years following harvesting.

Few studies have focused on the spatial distribution of wood in small streams as a result of streamside clearcut harvesting. In small streams the main factor that modifies the distribution of wood subsequent to forest harvesting is the occurrence or increased frequency of mass wasting events (Gomi et al. 2001, Millard 2000). As pointed out by Gomi et al. (2001), only landslides and debris flows modified the spatial distribution of instream wood in the steep headwater streams of their study. Limited movement of wood subsequent to harvesting is likely related to the high relative roughness, low transport capacities and occurrence of non-alluvial obstructions in these small streams (Hassan et al. 2005a).

This situation is in contrast to larger streams where several factors can contribute to the modification in the distribution of wood as result of streamside clearcut harvesting. These factors include the connectivity of hillslopes to the stream channel, and increased frequency of mass wasting events along with changes in stream reach and wood characteristics such as reduced channel bank stability due to loss of riparian trees, reduced lateral recruitment of trees, reduced piece size and subsequent decomposition and fragmentation of existing debris jams (e.g. Toews and Moore 1982; Hogan 1986, Bilby and Ward 1991; Ralph et al. 1994; Hogan et al. 1998). Cleaning of stream channels subsequent to harvesting can also increase the mobility of wood (Bilby 1984), which likely results in a modification of its spatial distribution.

Wildfire Disturbances and Stand Development Stage - It was also expected that wood distribution would change subsequent to wildfire disturbances with wood distributions being randomly distributed immediately subsequent to the episodic input of fire killed wood with more clumped wood accumulations forming over time as the fire killed wood became decomposed, fragmented and more mobile prior to inputs from chronic mortality associated with the regenerating post-fire riparian stand. This shift in spatial pattern over time was not observed and is likely related to the overall stability of wood in these small streams, the stability of stream banks, absence of debris flows and recruitment of new wood from regenerating riparian stands to replace wood that was either added by the wildfire or was already pre-existing in the stream prior to the wildfire disturbance.

This finding is in contrast to other studies (Minshall et al. 1997; Young 1994; Zelt and Wohl 2004 and Benda et al. 2003) where the mobility of wood increased subsequent to wildfires as result of increased streamflow, bank erosion, sediment transport and/or debris flows. Increased mobility of wood resulted in increased accumulation and clumping of wood (Zelt and Wohl 2004). This contrast is likely related to differences in channel characteristics and hillslope processes. For example, all of the mentioned studies were conducted in higher stream orders with streams widths greater than 5 m and several of these studies were situated in areas susceptible to erosion and hillslope mass wasting (e.g. debris flows). The streams in this study were observed to be quite robust with limited evidence of bank erosion and no evidence of mass wasting.

These findings are also supported by the relatively low amount of wood transported between each of the disturbance categories or stand development stages described in chapters 4 and 5. In those chapters it was shown that the amount of wood transported was relatively consistent between the four disturbance categories or stand development stages; therefore, the mobility and subsequent redistribution of wood would not be expected to change.

7.4.3 Reach Length Estimates and Power Analysis

Reach Length Estimates - The finding that a single stream reach approximately 1.4 to 2.5 times greater than the 150 m (30 to 50 bankfull widths) reach length used in this study is required to estimate wood volumes or abundance within 25% of the mean raises some important issues for future research or monitoring activities. A fundamental issue in sampling headwater streams is that study reaches are often physically limited by the uppermost extent of streams at which point streams become undefined. Similarly, in a downstream direction, the heterogeneity increases due to larger channel widths, increased stream power, variations in forest stand condition (e.g. changes in Biogeoclimatic zones from headwaters to lower reaches) and variations in the interplay of the various wood input and output processes. Also, disturbances such as wildfire or clearcutting may only span relatively small distances along stream channels until study reaches become undefined or influenced by changes in forest stand characteristics. For example, typical clearcut widths in the south-central interior of British Columbia are approximately 300 m wide in an upslope direction to optimize skid and haul road distances (i.e. conventional harvesting using road-side skidding as opposed to landings). Consequently, study reaches within clearcuts situated within headwater areas that are outside of the influence of forest edges are typically < 300 m (60 to 100 bankfull widths) given that stream channels mainly flow perpendicular to the general contours of the slope; therefore, limited stream length is available to sample these streams.

The required stream lengths (210 m to 420 m) identified in this study for estimation of wood volume or abundance within 25% of the mean are approximately 4 times shorter than stream lengths identified as being required in Young et al.'s (2006) study. This discrepancy is related to differences in study focus and the observed spatial arrangement of wood. For example, this study focused on characterizing wood loads in small streams whereas Young et al. (2006) estimated mean wood loads in the entire length of 3rd and 4th order streams, with sample lengths equaling or exceeding 1.5 km in 9 out of 14 of the streams sampled. The smaller channels and narrower focus of this study would have likely resulted in sampling of stream reaches that are more homogeneous in stream geomorphology, hydraulics and recruitment processes; conditions in wider and longer stream channels would understandably be more heterogeneous given higher variability in stream power, wood transport and streamside forest stand conditions. In addition, the spatial arrangement of wood in this study was found to be relatively well dispersed and random, with no stream reaches with little or no instream wood; in contrast Young et al. (2006) observed several reaches in all of the studied streams with little or no instream wood. These discrepancies highlight the need for further research and development of stratification procedures and protocols that combine traditional geomorphic stream classification systems (e.g. Montgomery and Buffington 1993; Rosgen 1994) with instream wood classification systems that better characterize the spatial arrangement of wood based on wood input, output and transport processes at various spatial and temporal scales.

The estimated reach lengths also have practical implications for forest management and development of wood storage/recruitment models. For example, if the purpose is to determine reference loads or targets (refer to Lisle 2002; Fox et al. 2003) that are required to meet certain thresholds that initiate forest management activities or regulatory consequences, then defensible and dependable thresholds must be based on meaningful wood load estimates. These estimates must take into account the spatial and temporal variability that can occur in wood loads and, therefore, must be based on estimates that adequately reflect stream and stand specific processes (Lisle 2002, Young et al. 2006). The above statement further highlights the need for the integration of geomorphic stream classification systems with instream wood classification systems to better characterize the spatial arrangement of wood in order to minimize uncertainty.

The high variability of wood loads observed in the small streams of this study may also limit field verification of wood storage/recruitment models; therefore, further research is required to better account for the processes and mechanisms that create such high variability in instream wood. This research need is particularly important in stream channels that appear to be homogenous in stream geomorphology and forest stand condition to ensure the actual level of homogeneity.

Power Analysis - Where significant differences were not identified in the comparisons of wood loads or geomorphic parameters (refer to Chapter 4, 5 and 6) between the various disturbance categories or stand development stages, caution should be used in concluding that group means were the same since there is a high probability of committing a Type II error due to small sample sizes and large error variances. Instead, the lack of observed differences should be considered inconclusive since much of the similarity is likely associated with the high sampling variability. On the other hand, where significant differences were identified, they are unlikely related to chance alone, especially since the Tukey-Kramer multiple comparison test that was used in comparison of group means is conservative and minimizes the risk of committing a Type I error (i.e. the error of rejecting a null hypothesis when it is actually true) (Neter et al. 1989).

The power analyses also raise some important issues for future studies or forest management/monitoring activities. In order to discuss these implications a brief description of power analysis is provided here. The purpose of power analysis is to ensure that sampling regimes are of sufficient size to ensure that statistical tests are adequate to detect a difference when there actually is a difference in reality: that is, minimizing the probability of not rejecting the null hypothesis when it is actually false (Zar 1999; Cohen 1988). As described by others (Cohen 1988; Zar 1999; Di Stefano 2001; Legg and Nagy 2006) power is related to effect size, error variance, sample size and Type I error rate (α). As described by Di Stefano (2001) the general form for the relation between power and the above mentioned parameters can be expressed as:

$$\text{Power} \propto \frac{\text{ES x } \alpha \text{ x } \sqrt{\text{n}}}{\sqrt{\sigma^2}}$$

where ES = effect size, α = Type I error rate, n = sample size and σ^2 = error variance. This equation shows that power increases with effect size, Type I error rate and sample size and decreases with variance (Di Stefano 2001).

In consideration of the above power analysis description the first sampling issue in comparison of instream wood loads is related to effect size. In this chapter, arbitrarily defined raw effect sizes were developed to detect small to large differences (20% to 80% difference) in mean wood loads in order to determine minimum sample sizes for a given level of power (i.e. 80%). These arbitrary effect sizes have limited environmental, geomorphic or biological basis or importance (Anticliffe 1999; Bryant et al. 2004). To date, limited information is available regarding effect sizes that are required to detect "biologically or geomorphically important" changes in stream channels. This issue is compounded by the fact that the biological or geomorphic role of instream wood is also dependant upon several factors which include the type of stream, presence/absence of various fish species, stream power and channel morphologies (e.g. bed particle sizes). Further study is required to develop meaningful biological or geomorphic measures of instream wood, especially in low gradient small streams similar to the south-central interior of British Columbia.

The second sampling issue relates to the Type I error rate (the probability of rejecting a true null hypothesis). This value is usually set arbitrarily at $\alpha = 0.05$ with $\beta = 0.20$ (power = 0.80), which assumes that making a Type I error is four times more serious than making a Type II error (Cohen 1988; Di Stefano 2001; Legg and Nagy 2006). Several authors (Peterman 1990; Sheppard 1999; Di Stefano 2001) have argued that more emphasis should be placed on avoiding Type II errors (the probability of accepting the null hypothesis when in fact it is false). For example, if a Type I error is made it is probably of less risk or cost to the environment since efforts to remedy the perceived problem would unlikely cause harm. In contrast, if a Type II error is committed environmental degradation could be missed with no remediation or management occurring that may lead to further degradation (Sheppard 1999; Di Stefano 2001; Legg and Nagy 2006). In the context of small stream management, this argument needs to be explored further to ensure longterm effects of streamside harvesting are not going unnoticed.

The third sampling issue relates to sample size, since larger sample sizes lead to increased power. Although a high level of effort was made to identify and sample a large number of study streams in this study, the reality was that very few study streams were actually available. In this study, small sample sizes were a major limitation in making conclusive statements regarding the effects of streamside clearcut harvesting. Future studies or monitoring activities should be aware of the limitations of sample size of this study and consideration should be given to developing approaches that can maximize the power of statistical inferences. These approaches may include alternative study designs such as BACI (before-and-after control impact) design, long-term monitoring sites or entire stream network surveys to better characterize the factors that influence instream wood.

The fourth and last sampling issue relates to error variance. Based on this study error variances between individual sample streams and group means were quite large even though a significant amount of effort was placed on selecting study streams that were geomorphologically homogeneous (refer to chapter 3, 4 and 5). Although it requires more study, much of the variation observed between sample streams may be related to forest stand conditions and dynamics (refer to Chapter 4 and 5); therefore, future studies need to focus on development of stratification systems to help further reduce variance.

7.5 CONCLUSION

Except at the smallest spatial scale (<3 m segments) the spatial distribution of instream wood followed a random pattern with no trend. There was limited evidence of increased mobility or accumulation of wood subsequent to streamside clearcut harvesting, stand replacing wildfires or riparian stand development. This observed random pattern is likely related to local wood recruitment processes associated with episodic or chronic tree mortality from adjacent riparian areas and the overall stability of wood in the small streams studied.

In addition, geomorphic processes such as debris flows or other mass wasting events are not a major factor in the redistribution of wood in small streams situated in the Okanagan Highlands or Thompson Plateau. This finding is in contrast to other studies conducted in steep headwater streams of the Pacific Northwest (e.g. Gomi et al. 2001; May and Gresswell 2003) where mass wasting events are the main factor in the redistribution of wood. This finding has important implications in the management of upslope areas outside of riparian areas within the study area since upslope areas do not play a role in the supply of wood to streams.

At smaller spatial scales (<3 m segments) departures from randomness were observed that were likely due to single tree interactions such as clumps of trees falling in the same location, one tree knocking over others and localized processes such as wind bursts, transport of smaller decayed pieces, disease and/or localized undercut banks. This finding highlights the need to consider several spatial scales when evaluating the distribution of wood since recruitment and output processes may vary with spatial scale due to the interaction between individual trees and smaller scale, localized mortality and recruitment.

Although identification of a random pattern validates the sample design and the application of parametric, univariate statistics that were used in this study, the observed wood load data were highly variable. As result of this variability, study reach lengths of 84 to 140 bankfull widths would be required to estimate mean wood volumes within 25% of the mean for the 3 m to 5 m wide streams assessed in this study. Similarly, 42 to 70 bankfull widths would be required to estimate wood abundance within 25% of the mean. This equates to reach lengths that are approximately 1.4 to 2.5 times greater than were utilized in this study.

Caution must be exercised in accepting the null hypothesis of no logging impacts in the comparison of wood loads (refer to Chapter 4 and 5) due to the low power associated with small sample sizes and high variability. However, where significant differences were identified in comparison of disturbance categories or stand development stages, the actual group differences observed are unlikely related to chance alone. Low power will likely be a common issue for future studies or monitoring activities related to instream wood due to high variability (Craig and Roberts 2005); therefore, careful attention should be given to study planning and sampling design to ensure sufficient statistical power for improved statistical inference.

Table 7.1. Summary of tests of independence used in evaluating the spatial distribution of wood (volume, abundance and distance between wood pieces) in relation to the four disturbance categories (OF, WF, H90, H70).

Contingency Table Layout (R x C) Row (R)	X	Column (C)	Contingency Table Description	Statistical Tests Used
Pattern (volume and abundance) Stratum 3 m subsection 5 m subsection 10 m subsection		Disturbance Category	Unordered Stratified R X C Contingency Table	Cochran-Mantel- Haenszel (CMH) Test Type: Asymptotic Monte Carlo
Trend (volume and abundance) Stratum 3 m subsection 5 m subsection 10 m subsection		Disturbance Category	Unordered Stratified R X C Contingency Table	Cochran-Mantel- Haenszel (CMH) Test Type: Asymptotic Monte Carlo
Pattern (Distance Difference)		Disturbance Category	Unordered R X C Contingency Table	Fisher's Exact Test Type: Asymptotic Monte Carlo
Trend (Distance Difference)		Disturbance Category	Unordered R X C Contingency Table	Fisher's Exact Test Type: Asymptotic Monte Carlo

Table 7.2. Summary of tests of independence used in evaluating spatial distribution of wood (volume, abundance and distance between wood pieces) in relation to the four stand development stages from youngest to oldest (0-50, 51-100, 101-150, 151-200 years).

Contingency Table Layout (R x C) Row (R)	X Column (C)	Contingency Table Description	Statistical Tests Used
Pattern (volume and abundance) Stratum 3 m subsection 5 m subsection 10 m subsection	Stand Development Stage (Order maintained youngest to oldest)	Singly Ordered Stratified R X C Contingency Table	Cochran-Mantel- Haenszel (CMH) Test Type: Asymptotic Monte Carlo
Trend (volume and abundance) Stratum 3 m subsection 5 m subsection 10 m subsection	Stand Development Stage (Order maintained youngest to oldest)	Singly Stratified R X C Contingency Table	Cochran-Mantel- Haenszel (CMH) Test Type: Asymptotic Monte Carlo
Pattern (Distance Difference)	Disturbance Category (Order maintained youngest to oldest)	Singly Ordered R X C Contingency Table	Kruskal-Wallis Test Type: Asymptotic Monte Carlo
Trend (Distance Difference)	Disturbance Category (Order maintained youngest to oldest)	Singly Ordered R X C Contingency Table	Kruskal-Wallis Test Type: Asymptotic Monte Carlo

Table 7.3. Runs Test results for wood volume for the three subsection scales.

Pattern	Number of Study Reaches		
	3 m Subsection	5 m Subsection	10 m Subsection
Random	34	37	37
Non-Random	4	1	1

Table 7.4. Runs Test results for wood abundance for the three subsection scales.

Pattern	Number of Study Reaches		
	3 m Subsection	5 m Subsection	10 m Subsection
Random	35	38	38
Non-Random	3	0	0

Table 7.5. Runs Test and Mann-Kendall Test results for the distance between wood pieces in each study stream. Direction of trend in an upstream direction is also shown in brackets.

Runs Test Results		Mann-Kendall Test Results	
Random	31	Trend Significant	3 (3 +ve, 0 –ve)
Non-Random	7	No Trend	35

Table 7.6. Mann-Kendall Test results for wood volume for the three subsection scales tested.

Trend	Number of Study Reaches		
	3 m Subsection	5 m Subsection	10 m Subsection
Trend Significant	4 (4 +ve, 0 –ve)	3 (3 +ve, 0 –ve)	8 (3 +ve, 5 –ve)
No Trend	34	35	30

Table 7.7. Mann-Kendall Test results for wood abundance for the three subsection scales tested. Values in brackets indicate the number of study reaches with positive or negative trend in an upstream direction.

Trend	Number of Study Reaches		
	3 m Subsection	5 m Subsection	10 m Subsection
Trend Significant	3 (3 +ve, 0 –ve)	3 (3 +ve, 0 –ve)	10 (4 +ve, 6 –ve)
No Trend	35	38	28

Table 7.8. Stratified contingency table of wood volume showing combined frequencies of Runs Test results by pattern, disturbance category and stratified by subsection length.

Pattern	Subsection Length	OF	WF	H90	H70
		Disturbance Category			
Random	3 m	7	5	7	5
	5 m	8	6	7	5
	10 m	8	6	7	5
Non-Random	3 m	1	1	0	0
	5 m	0	0	0	0
	10 m	0	0	0	0

Table 7.9. Stratified contingency table of wood abundance showing combined frequencies of Runs Test results by pattern, disturbance category and stratified by subsection length.

Pattern	Subsection Length	OF	WF	H90	H70
		Disturbance Category			
Random	3 m	7	6	6	5
	5 m	8	6	7	5
	10 m	8	6	7	5
Non-Random	3 m	1	0	1	0
	5 m	0	0	0	0
	10 m	0	0	0	0

Table 7.10. Stratified contingency table of wood volume showing combined frequencies of Mann-Kendall Test results by trend, disturbance category and stratified by subsection length.

Trend	Subsection Length	OF	WF	H90	H70
		Disturbance Category			
No Trend	3 m	8	5	6	5
	5 m	8	5	6	5
	10 m	7	4	7	3
Trend Significant	3 m	0	1	1	0
	5 m	0	1	1	0
	10 m	1	2	0	2

Table 7.11. Stratified contingency table of wood abundance showing combined frequencies of Mann-Kendall Test results by trend, disturbance category and stratified by subsection length.

Trend	Subsection Length	Disturbance Category OF	WF	H90	H70
No Trend	3 m	8	5	6	5
	5 m	8	5	6	5
	10 m	7	4	6	3
Trend	3 m	0	1	1	0
Significant	5 m	0	1	1	0
	10 m	1	2	1	2

Table 7.12. Contingency table (2 x 4) of distance differences between wood pieces showing frequencies of Runs Test results by pattern and disturbance category.

Pattern	Disturbance Category			
	OF	WF	H90	H70
Random	7	4	6	5
Non-Random	1	2	1	0

Table 7.13. Contingency table (2 x 4) of distance differences between wood pieces showing frequencies of Mann-Kendall test results by trend and disturbance category.

Trend	Disturbance Category			
	OF	WF	H90	H70
No Trend	7	5	6	5
Trend Significant	1	1	1	0

Table 7.14. Summary of statistical results from various tests of independence used in evaluating the spatial distribution of wood (volume, abundance and distance difference) in relation to the four disturbance categories (OF, WF, H90, H70).

Contingency Table Layout (R x C) Row (R)	X Column (C)	Test / Type	Statistic	p-value (2-sided)
Pattern (volume)	Disturbance	CMH Test		
Stratified by	Category	Asymptotic	1.866	0.601
subsection interval		Monte Carlo	1.866	0.826
Pattern (abundance)	Disturbance	CMH Test		
Stratified by	Category	Asymptotic	1.544	0.672
subsection interval		Monte Carlo	1.544	1.000
Pattern (Distance	Disturbance	Fisher's Exact Test		
Difference)	Category	Asymptotic	2.244	0.523
		Monte Carlo	2.244	0.616
Trend (volume)	Disturbance	CMH Test		
Stratified by	Category	Asymptotic	3.388	0.336
subsection interval		Monte Carlo	3.388	0.341
Trend (abundance)	Disturbance	CMH Test		
Stratified by	Category	Asymptotic	3.001	0.392
subsection interval		Monte Carlo	3.001	0.408
Trend (Distance	Disturbance	Fisher's Exact Test		
Difference)	Category	Asymptotic	2.078	0.556
		Monte Carlo	2.078	0.834

Table 7.15. Stratified contingency table of wood volume showing combined frequencies of Runs Test results by pattern, stand development stage and stratified by subsection length.

Pattern	Subsection Length	Stand Development Stage (years) 0-50	51-100	101-150	151-200
Random	3 m	5	7	5	5
	5 m	6	7	6	6
	10 m	6	7	6	6
Non-Random	3 m	1	1	1	1
	5 m	0	1	0	0
	10 m	0	1	0	0

Table 7.16. Stratified contingency table of wood abundance showing combined frequencies of Runs Test results by pattern, stand development stage and stratified by subsection length.

Pattern	Subsection Length	Stand Development Stage (years) 0-50	51-100	101-150	151-200
Random	3 m	6	8	5	5
	5 m	6	8	6	6
	10 m	6	8	6	6
Non-Random	3 m	0	0	1	1
	5 m	0	0	0	0
	10 m	0	0	0	0

Table 7.17. Stratified contingency table of wood volume showing combined frequencies of Mann-Kendall Test results by trend, stand development stage and stratified by subsection length.

Trend	Subsection Length	Stand Development Stage (years) 0-50	51-100	101-150	151-200
No Trend	3 m	5	7	5	6
	5 m	5	7	6	6
	10 m	4	5	6	5
Trend Significant	3 m	1	1	1	0
	5 m	1	1	0	0
	10 m	2	3	0	1

Table 7.18. Stratified contingency table of wood abundance showing combined frequencies of Mann-Kendall Test results by trend, stand development stage and stratified by subsection length.

Trend	Subsection Length	Stand Development Stage (years) 0-50	51-100	101-150	151-200
No Trend	3 m	5	7	6	6
	5 m	5	7	6	6
	10 m	4	4	6	5
Trend Significant	3 m	1	1	0	0
	5 m	1	1	0	0
	10 m	2	4	0	1

Table 7.19. Contingency table (2 x 4) of distance differences between wood pieces showing frequencies of Runs Test results by pattern and stand development stage.

Pattern	**Stand Development Stage (years)**			
	0-50	**51-100**	**101-150**	**151-200**
Random	4	6	5	5
Non-Random	2	2	1	1

Table 7.20. Contingency table (2 x 4) of distance differences between wood pieces showing frequencies of Mann-Kendall test results by trend and stand development stage.

Trend	**Stand Development Stage (years)**			
	0-50	**51-100**	**101-150**	**151-200**
No Trend	5	7	5	6
Trend Significant	1	1	1	0

Table 7.21. Summary of statistical results from various tests of independence used in evaluating the spatial distribution of wood (volume, abundance and distance between wood pieces) in relation to the four stand development stages (0-50, 51-100, 101-150, 151-200).

Contingency Table Layout (R x C)		**Test / Type**	X^2	**p-value (2-sided)**
Row (R)	**X Column (C)**			
Pattern (volume)	Stand	CMH Test		
Stratified by	Development	Asymptotic	0.055	0.814
subsection interval	Stage	Monte Carlo	0.055	0.837
Pattern (abundance)	Stand	CMH Test		
Stratified by	Development	Asymptotic	1.811	0.178
subsection interval	Stage	Monte Carlo	1.811	0.201
Pattern (Distance	Stand	Kruskal-Wallis Test		
Difference)	Development	Asymptotic	0.570	0.450
	Stage	Monte Carlo	0.570	0.508
Trend (volume)	Stand	CMH Test		
Stratified by	Development	Asymptotic	3.325	0.068
subsection interval	Stage	Monte Carlo	3.325	0.071
Trend (abundance)	Stand	CMH Test		
Stratified by	Development	Asymptotic	4.667	**0.031**
subsection interval	Stage	Monte Carlo	4.667	**0.028**
Trend (Distance	Stand	Kruskal-Wallis Test		
Difference)	Development	Asymptotic	0.558	0.455
	Stage	Monte Carlo	0.558	0.599

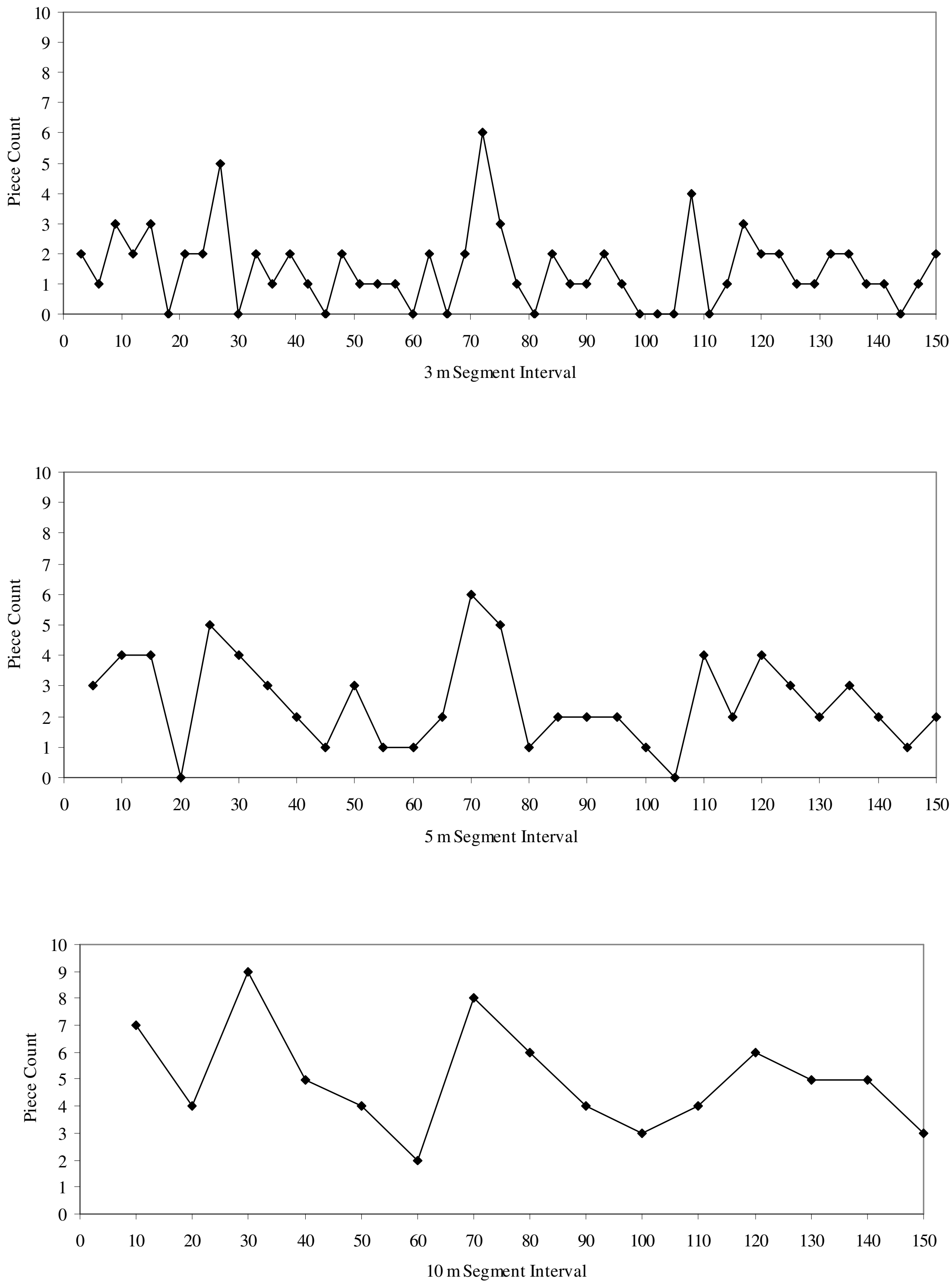


Figure 7.1. Example of a typical random distribution of wood abundance from the 38 study streams showing the three different subsection intervals (example used CANTRIB1).

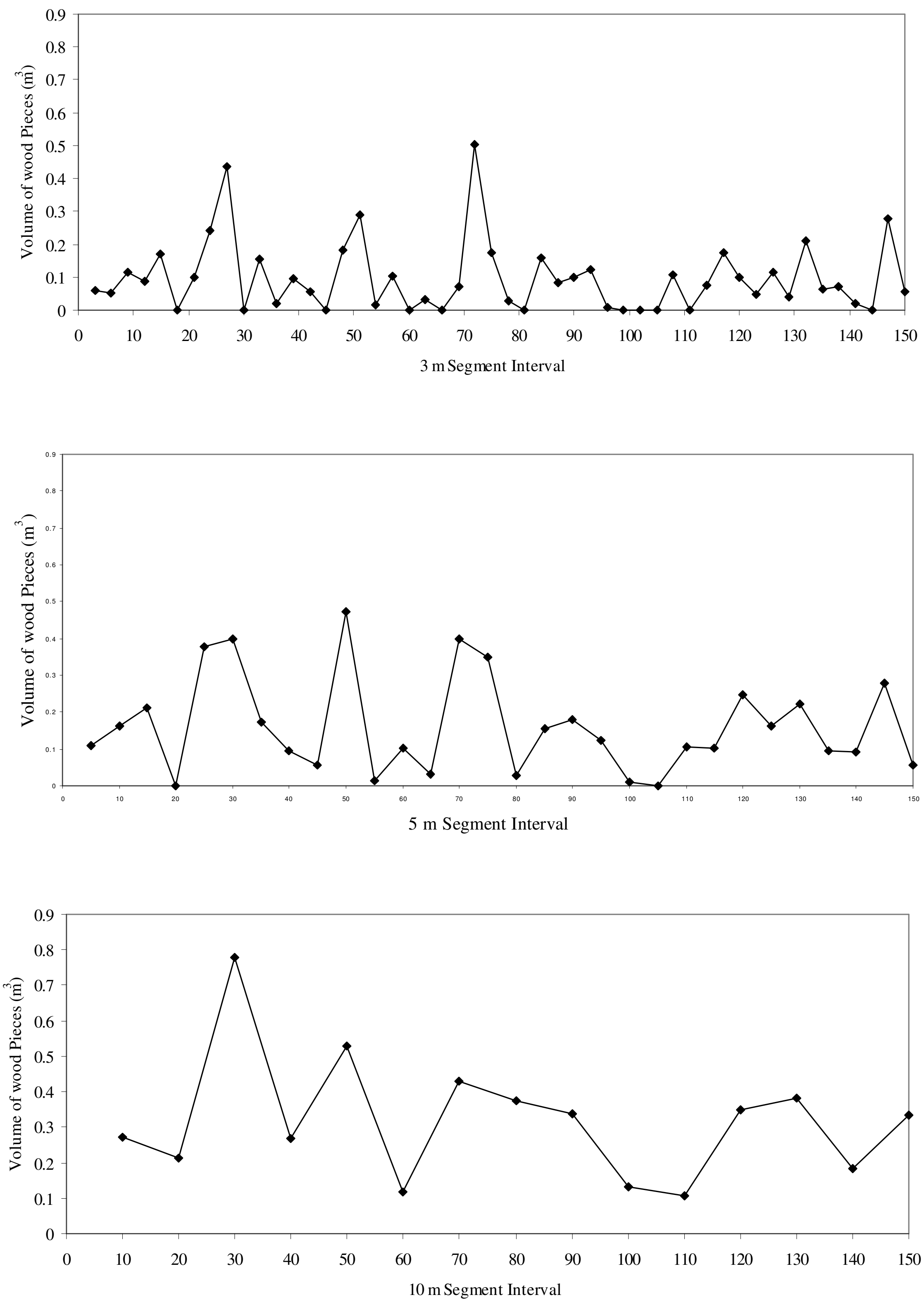


Figure 7.2. Example of a typical random distribution of wood volume from the 38 study streams showing the three different subsection intervals (example used CANTRIB1).

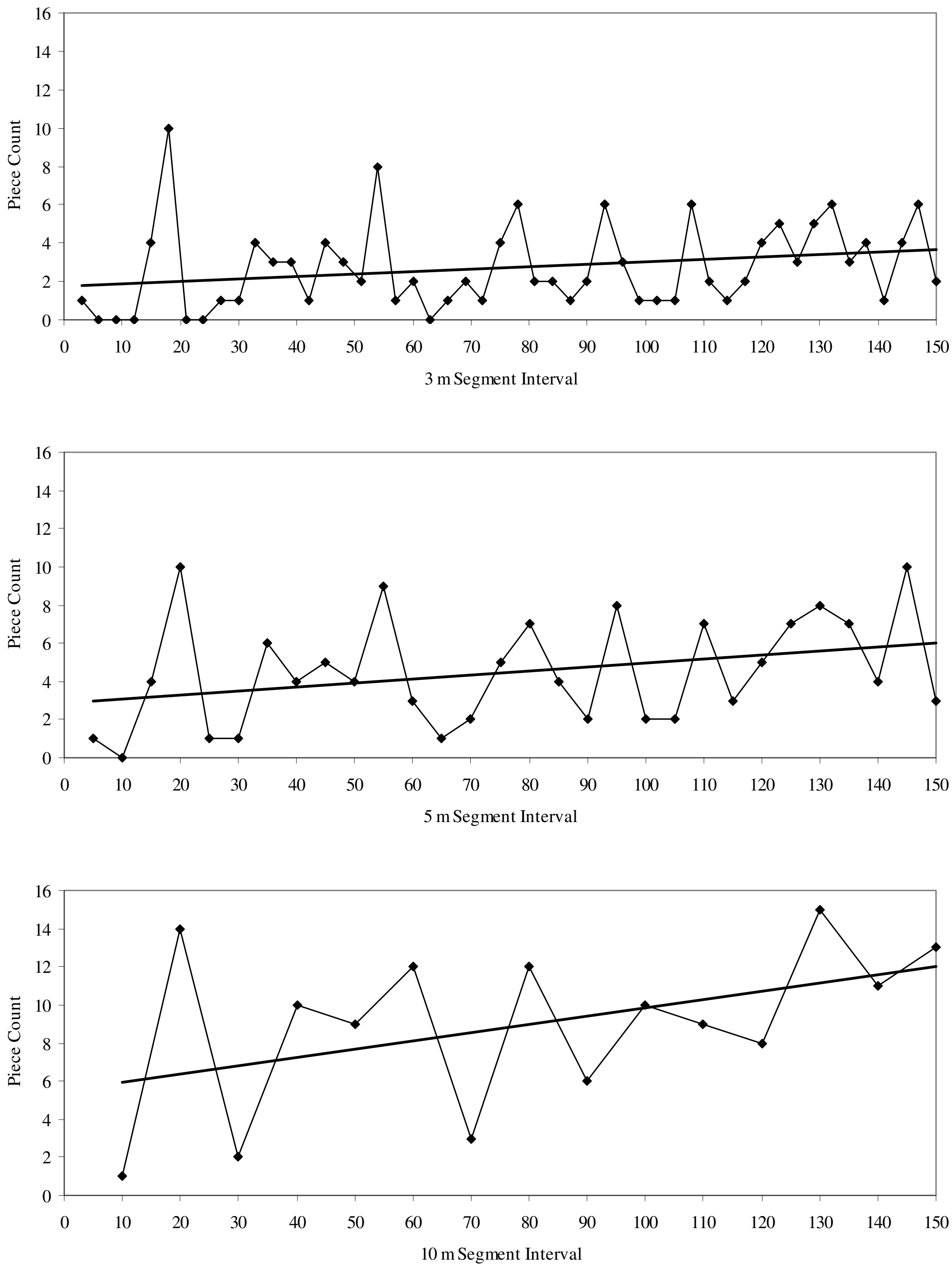


Figure 7.3. Example of wood abundance distribution with significant trend (trendline shown) for the three different subsection intervals (example used PASAYTEN1).

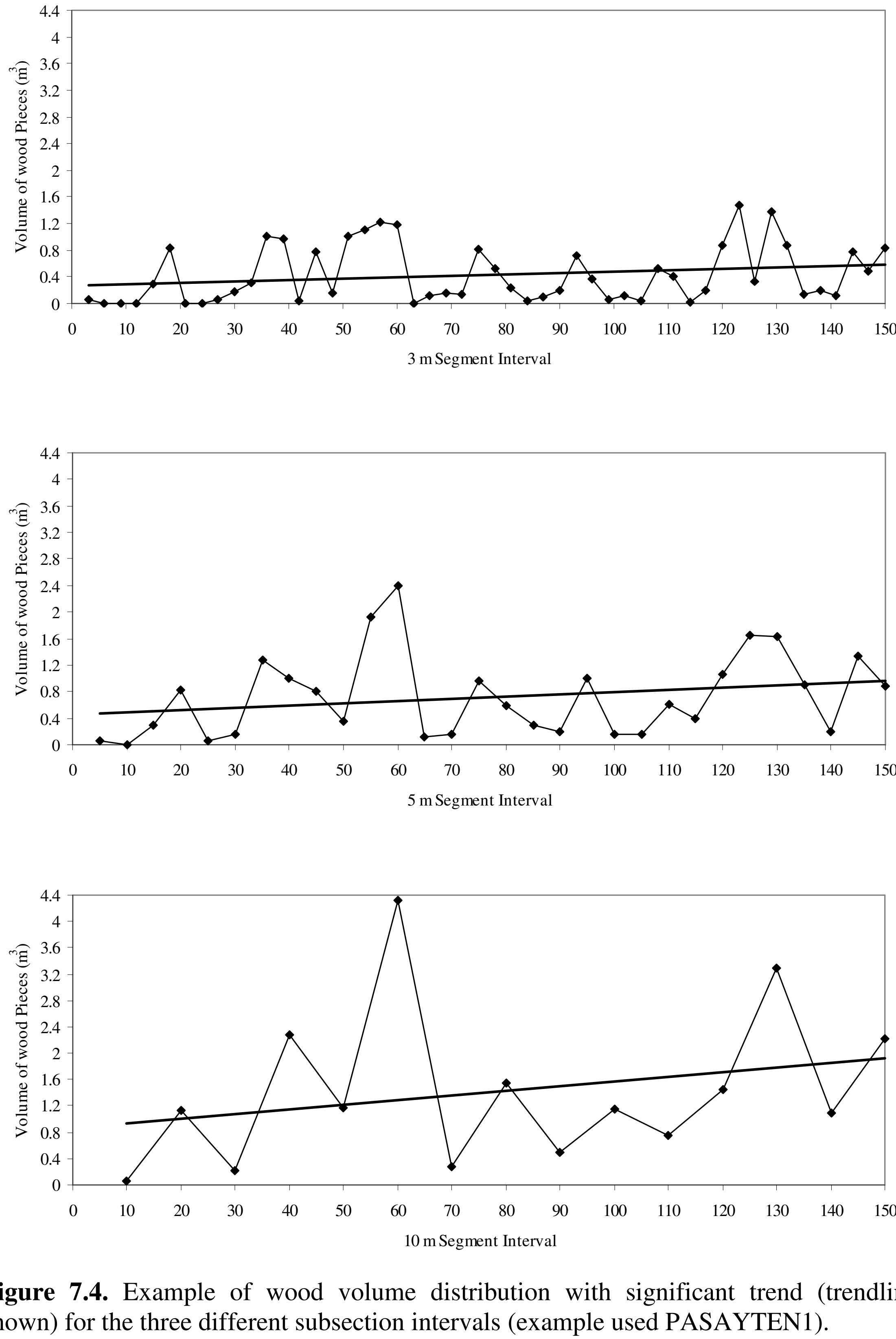


Figure 7.4. Example of wood volume distribution with significant trend (trendline shown) for the three different subsection intervals (example used PASAYTEN1).

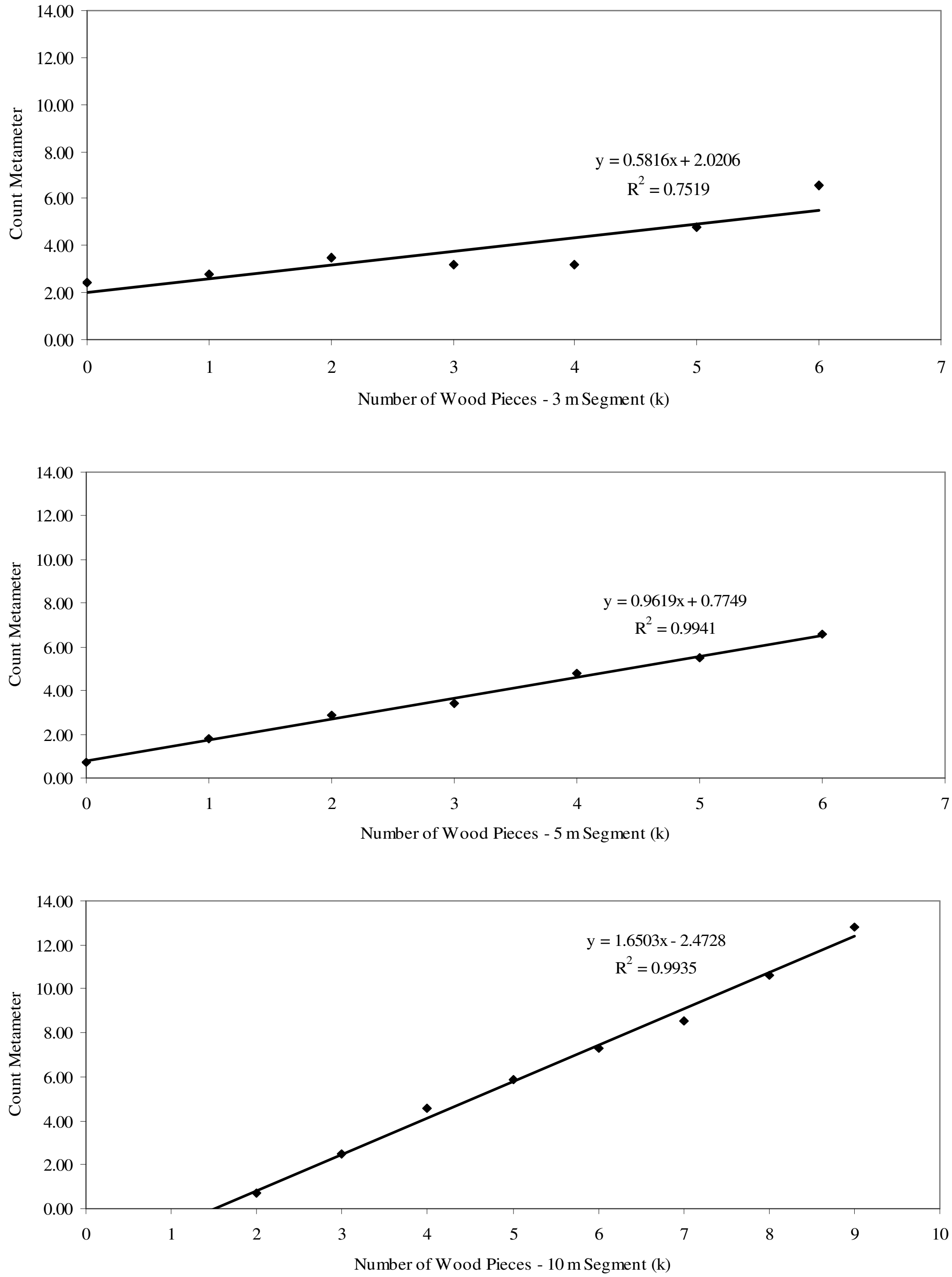
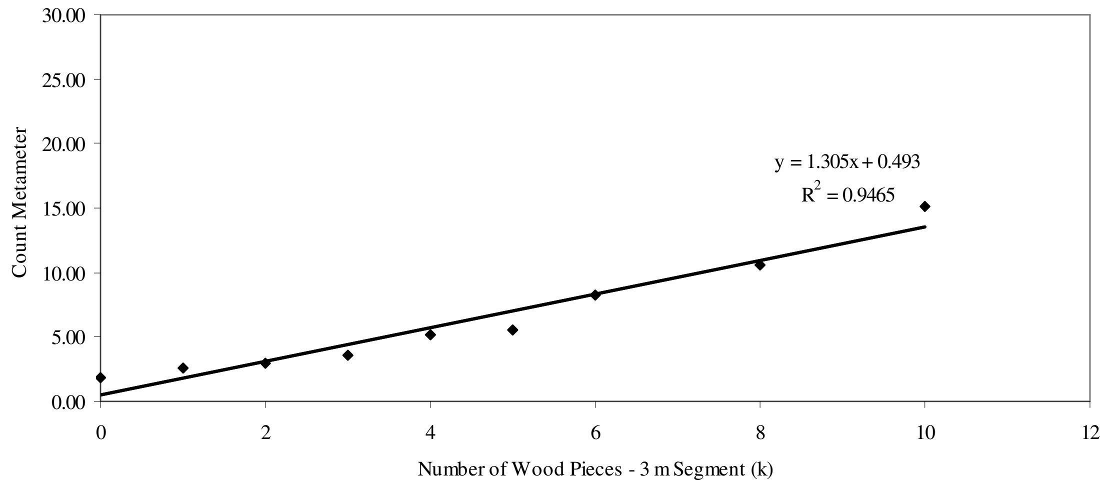
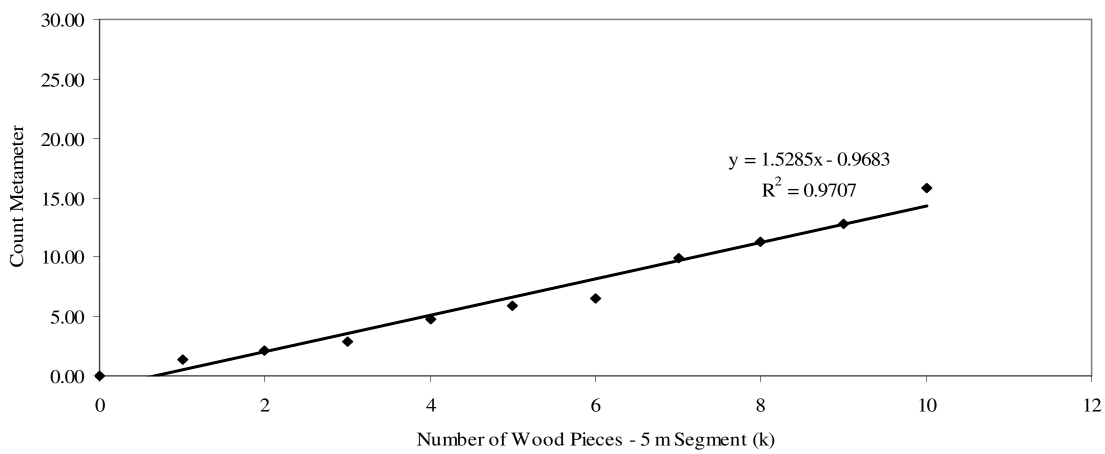


Figure 7.5. Poissonness Plot of wood abundance for each of the three subsection intervals (example used CANTRIB1). The data fit the Poisson distribution reasonably well except the plot showing the smaller, 3 m subsection interval indicates a poor fit with the Poisson distribution. Refer to Hoaglin (1980) and Friendly(2000) for description (Count Metermeter = $\text{Log}(x_k)+\text{Log}(k!)$).





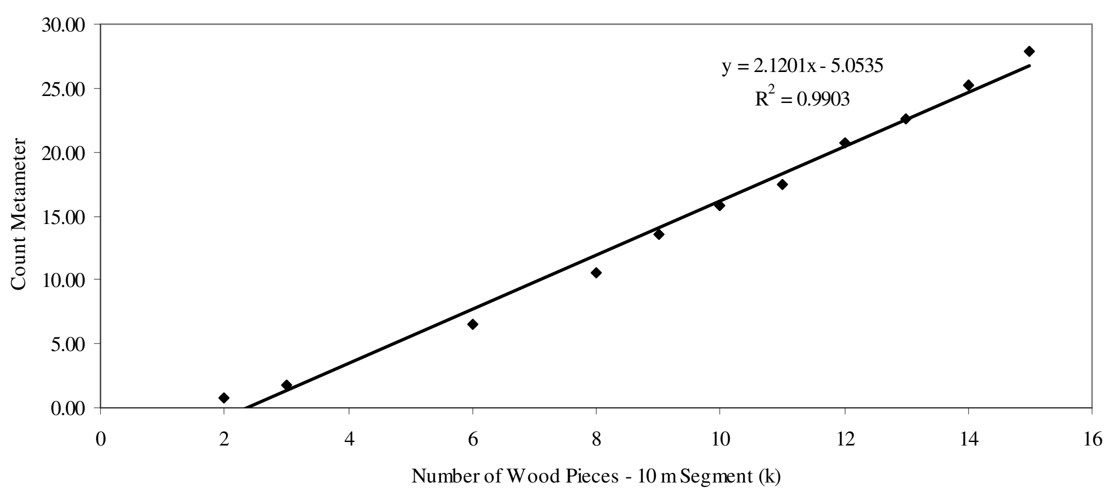


Figure 7.6. Poissonness plot of wood abundance for each of the three subsection intervals (example used PASAYTEN1). The data fit the Poisson distribution reasonably well. Refer to Hoaglin (1980) and Friendly(2000) for description (Count Metermeter = $\text{Log}(x_k)+\text{Log}(k!)$).

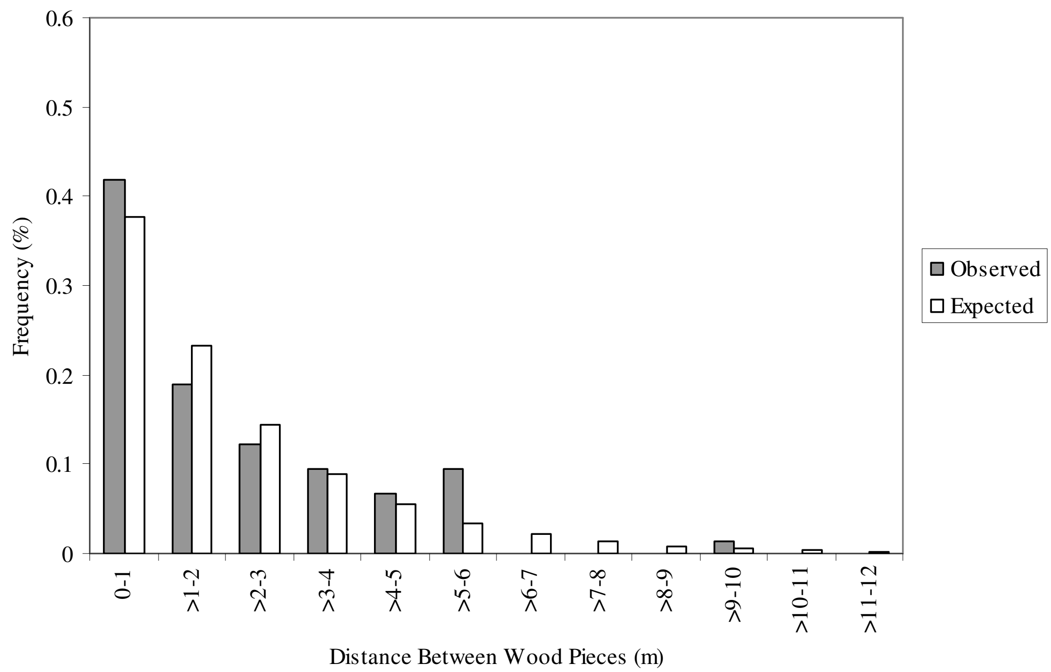


Figure 7.7. Observed frequency distribution of the distance between consecutive wood pieces fitted against expected exponential distribution (Example used CANTRIB1). In this case the observed distribution follows an exponential distribution ($p = 0.503$).

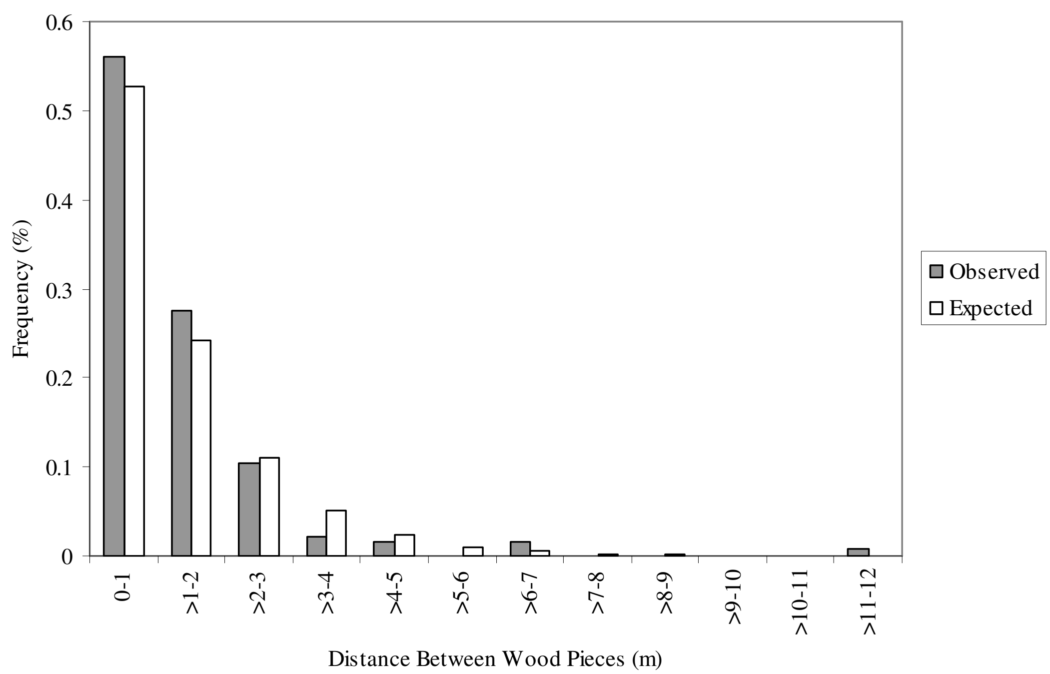


Figure 7.8. Observed frequency distribution of the distance between consecutive wood pieces fitted against expected exponential distribution (Example used PASAYTEN1). In this case a poor fit was found between the observed distribution and an exponential distribution ($p<0.001$).

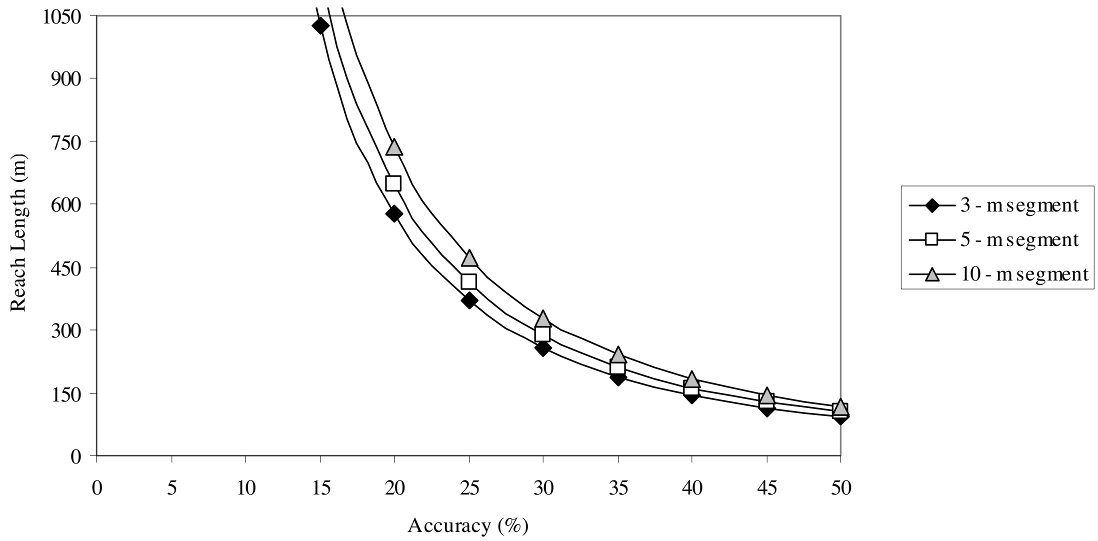


Figure 7.9. Reach length required to sample wood volume within a certain percent uncertainty of the mean based on the three subsection intervals (3 m segment, 5 m segment and 10 m segment).

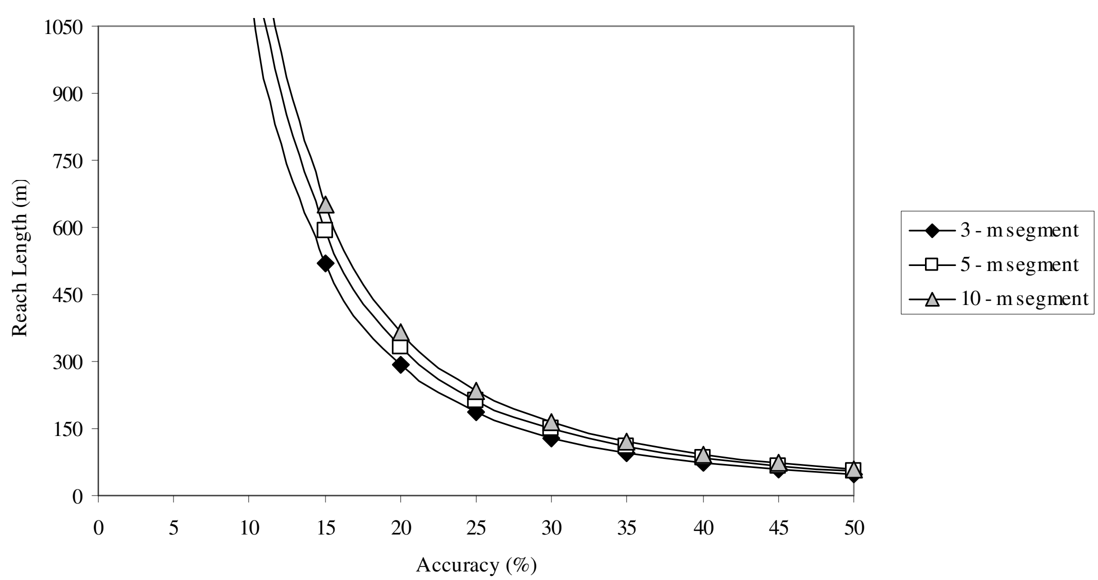


Figure 7.10. Reach length required to sample wood abundance within a certain percent uncertainty of the mean based on the three subsection intervals (3 m segment, 5 m segment and 10 m segment).

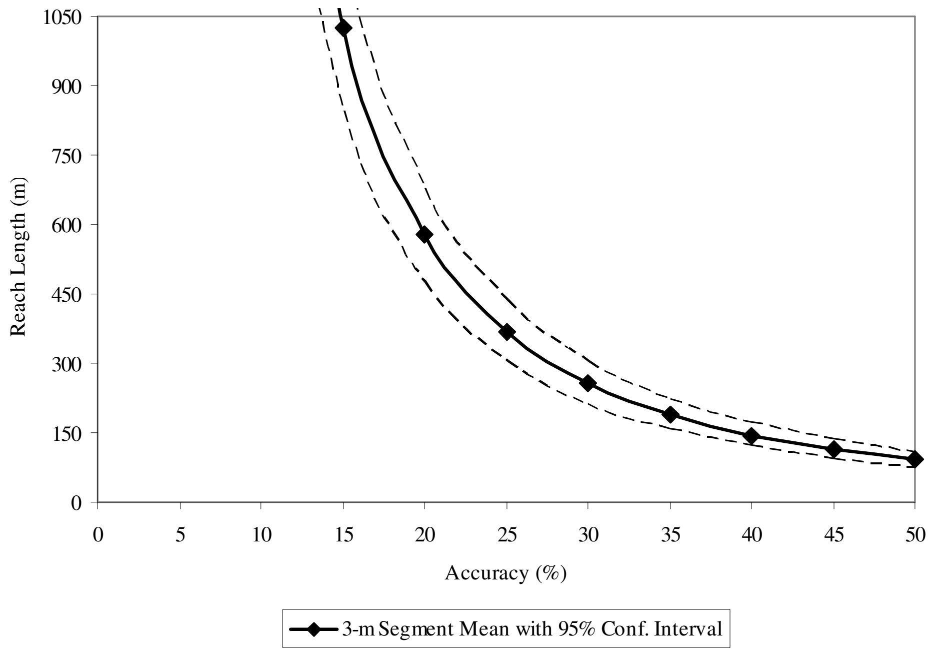


Figure 7.11. Reach length required to sample wood volume within a certain percent uncertainty of the mean based on the 3 m subsection interval. Hashed lines represent upper and lower 95% confidence interval around mean reach length based on sample size estimates from all 38 study streams.

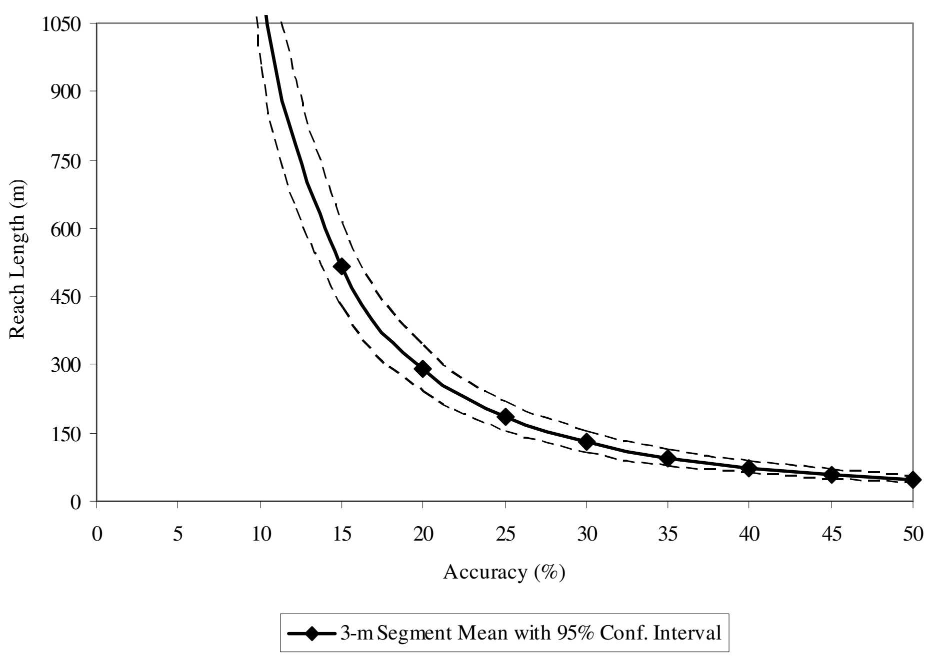


Figure 7.12. Reach length required to sample wood abundance within a certain percent uncertainty of the mean based on the 3 m subsection interval. Hashed lines represent upper and lower 95% confidence interval around mean reach length based on sample size estimates from all 38 study streams.

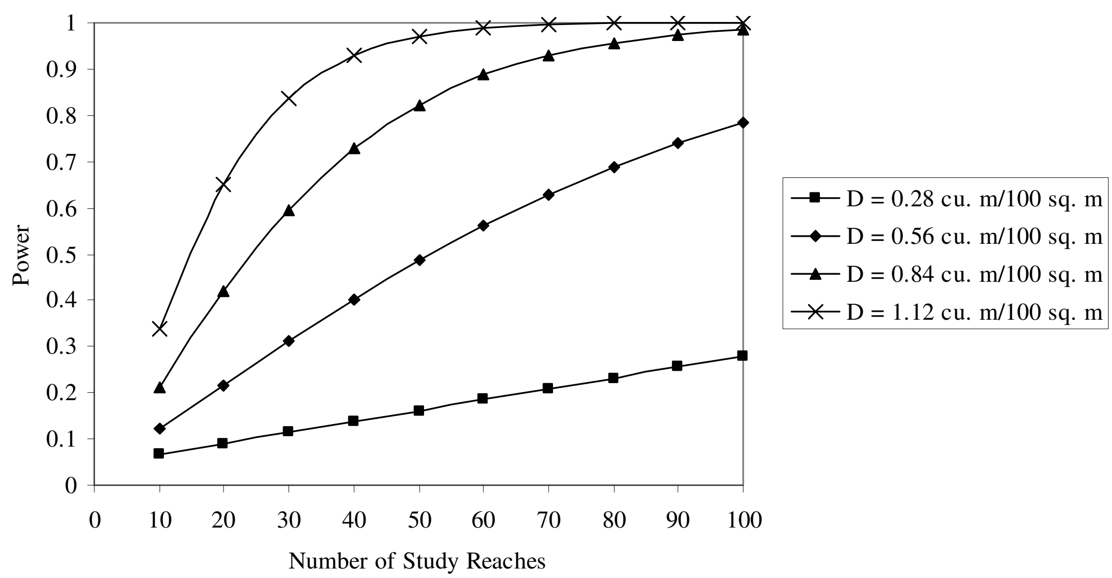


Figure 7.13. Power curves showing the number of 150 m study reaches required to compare instream wood volumes in streams flowing through clearcut harvested and undisturbed, older forested areas given different mean differences (D). Power calculations based on $\sigma = 1.02$ m^3/100 m^2.

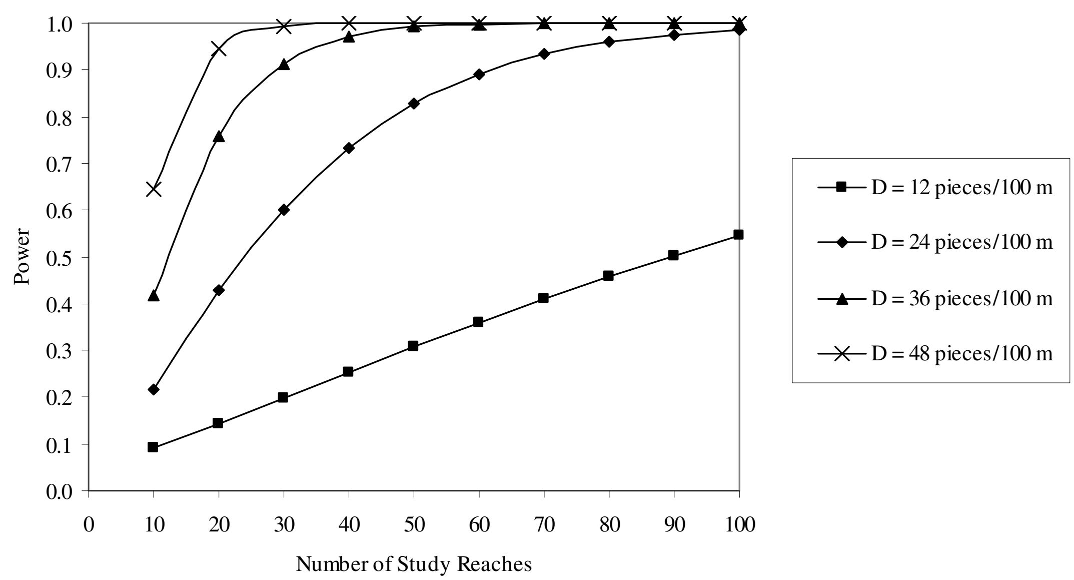


Figure 7.14. Power curves showing the number of 150 m study reaches required to compare instream wood abundance in streams flowing through clearcut harvested and undisturbed, older forested areas given different mean differences (D). Power calculations based on $\sigma = 28.62$ pieces/100 m.

CHAPTER 8

CONCLUSION

8.1 SUMMARY

The primary goal of this research was to address knowledge gaps regarding small streams and the temporal, spatial and geomorphic dynamics of instream wood in forest stand types that are dominated by relatively frequent stand replacing wildfires and low gradient, decoupled headwater streams that infrequently experience mass wasting events. This research compared the quantity and characteristics of instream wood between streams flowing through riparian areas that were in various stages of stand development (Chapter 4) or had experienced either wildfire disturbances or streamside clearcut harvesting (Chapter 5). Various characteristics of channel morphology and the geomorphic role of wood were also compared in relation to the different riparian conditions and disturbance histories (Chapter 6). The spatial distribution of wood in relation to stand development stage, wildfire disturbance and streamside clearcut harvesting were also examined (Chapter 7). Analysis of the spatial distribution of wood included an evaluation of study reach lengths and sample sizes used in this study to improve future studies or forest management/monitoring activities (Chapter 7). This research provided new field-based information that can be used in the management of small streams and provide a clearer linkage between various riparian stand conditions, instream wood loads and small stream geomorphology that occur within the south-central interior of British Columbia. A summary of key findings from this research and recommendations for further research are provided below.

8.2 SUMMARY OF KEY FINDINGS

8.2.1 Wood Loads and Geomorphology in Relation to Stand Development Stage (Chapter 4 and 6)

Few, if any, field studies have been conducted that have focused on the temporal trend of the storage and characteristics of instream wood associated with major stand replacing wildfire disturbances and subsequent stand development stages. In response to this lack of information a chronosequence of instream wood loads (volume and number) were sampled in 26 small streams flowing through riparian forest stands ranging in age between 32 to 200 years old to reconstruct (i.e. space for time substitution) the temporal trend in wood loading subsequent to stand-replacing wildfire disturbances. A distinct temporal trend in wood loading was observed with elevated wood loads present 30-50 years subsequent to the wildfire disturbances with wood volume following a "reverse J-shaped" trend in relation to time since the last major fire disturbance. The number of wood pieces followed a similar trend but was highly variable in relation to the time since the last major wildfire disturbance. Several wood characteristics (i.e. orientation, position, input source and decay state) were also evaluated in relation to various stand development stages subsequent to stand replacing wildfire disturbances. Although wood was observed to play an important functional role in these channels, few characteristics were altered in relation to the time since the last major wildfire disturbance, suggesting that these stream channels are relatively robust to changes in instream wood due to past wildfire disturbances. Similarly, channel morphology characteristics were not different in relation to stand development stage, providing no evidence of temporal changes in channel morphology. Instream wood volume was determined to persist 90 to 100 years subsequent to the major wildfire disturbance based upon an exponential decay function of wood volume and a calculated depletion rate coefficient of 0.05.

This research showed that historically in absence of human influence (e.g. fire suppression) wood loads in small streams would not have been static and would have been quite dynamic in relation to historic wildfire disturbances. Knowledge of the long-term dynamics of instream wood provides an important basis for understanding the historic range of variability of instream wood and can be used in the design of forest management strategies that emulate natural disturbance.

Much attention has been focused on the modeling of wood storage dynamics (e.g. Gregory et al. 2003) through time or space; however, few of these models have been developed to assess the implications of altered wood loads on channel morphology. In my study limited temporal evidence of altered channel morphology was observed in response to the differences in wood loading observed between wildfires, streamside clearcut harvesting or stand development stage. This finding highlights the importance of considering factors such as the inherent stability of stream channels and management history (stream cleaning versus non-cleaned streams) of streams in evaluating instream wood loads.

Wood inputs to the small streams were observed to be generated from local sources directly adjacent to the stream channel with a lack of evidence suggesting that upslope sources contributed wood to streams. This finding comes in light of numerous recent studies (e.g. May and Gresswell 2003; May 2007) from steep headwater streams that have highlighted the requirement for improved management of upslope areas in order to avoid altering instream wood loads.

8.2.2 Wood Loads and Geomorphology in Relation to Streamside Clearcut Harvesting and Wildfire Disturbance (Chapters 5 and 6)

Instream wood loads (volume and number) and characteristics were compared between wildfire disturbed, clearcut harvested, and undisturbed riparian forest stands. A total of 26 study streams with bankfull widths less than 5 m were surveyed and grouped into four categories (i.e. old forest, wildfire, recent clearcuts and old clearcuts) for comparison. Total instream wood volumes were three times higher in the streams disturbed by wildfire as compared to the older riparian forest stands, confirming that wildfire disturbance is an important mechanism to recruit wood into streams. No significant differences in total wood volumes were identified between any of the remaining categories. Also, no significant differences in the total number of wood pieces were found between any of the four disturbance categories. Contrary to expectation, the observed results did not show significant reductions in the number of pieces or volume of instream wood subsequent to streamside clearcut harvesting over the short-term (<30-40 years). This finding is most likely related to the low transport capacity in these study streams, retention of non-merchantable trees and recruitment of slash subsequent to harvesting.

Although wood loads did not differ, the decay condition and position of wood in the clearcut sites was quite different from the other study sites. For instance, in the older clearcut sites, a higher proportion of wood was in an advanced state of decay, and there were a reduced number of wood pieces spanning the channel. This finding highlights the importance of not only assessing the amount of wood but also the characteristics of wood since over the longterm these characteristics may provide important insight into the longterm implications of streamside clearcut harvesting. Over the longterm the streamside clearcut harvested streams channels are likely more susceptible to altered channel morphology given the higher degree of wood decay and the lack of new wood inputs.

No significant differences in channel morphology were observed between the various disturbance categories likely reflecting the inherent stability of the channels included in this study; however, the amount of fine bed particles (particles < 8 mm) were observed to be higher in the older (1960s to 1970s) streamside clearcut harvested streams and the wildfire disturbed streams. Direct evidence for the higher fine bed particles was limited; however, presence of deteriorating road crossings and roads that were built to a lower standard (e.g. poor drainage management with encroachment of roads in riparian areas) are most likely contributors in the older streamside clearcut harvested streams. Similarly, wildfire has been shown to have a strong influence on erosional processes with fires often resulting in surface erosion from overland flow (Wondzell and King 2003) which may account for the elevated fine bed particle sizes observed in the wildfire disturbed streams.

8.2.3 Spatial Arrangement of Wood in Relation to Disturbances and Stand Development (Chapter 7)

Except at the smallest spatial scale (< 3 m segment), instream wood was arranged in a random pattern in the majority of streams (>90%) with few streams showing a trend in wood loading. The observed spatial distribution provides strong evidence of a "dispersed source control pattern" (Swanson 2003) that is characteristic of streams with low transport capacities and random dispersed sources. In addition, no evidence was found to suggest that the random arrangement of wood had changed in response to streamside clearcut harvesting, wildfire disturbance or in relation to stand development stage highlighting the importance of local recruitment of wood from adjacent riparian areas in association with either episodic or chronic tree mortality. This finding has important implications for management of upslope areas since geomorphic processes such as debris flows or other mass wasting events were not a major factor in the redistribution of wood in the small streams of this study.

At the smallest spatial scale (<3 m segments), departures from randomness were observed that were likely due to single tree interactions, such as clumps of trees falling in the same location, one tree knocking over others and localized processes such as wind bursts, transport of smaller decayed pieces, disease and/or localized undercut banks. This finding highlights the need to consider several spatial scales when evaluating the distribution of wood since recruitment and output processes may vary with spatial scale due to the interaction between individual trees and smaller scale, localized mortality and recruitment.

8.2.4 Sample Reach Length and Sample Size (Chapter 7)

Sample lengths of 150 m (30 to 50 bankfull widths) were initially assumed to be sufficient to adequately characterize mean wood loads (volume and abundance) in individual study streams. This initial assumption was based on previous channel morphology studies (e.g. Platts 1983; Simonson et al. 1994; Robison 1997) that have shown reach lengths of 30 to 50 bankfull widths were adequate. At this length, mean wood volumes and abundance were estimated in this study to be within 30 to 40% of the true mean. For higher precision, reach lengths of 420 m (84 to 140 bankfull widths) would be required to estimate wood volumes within 25% of the mean and reach lengths of 210 m (42 to 70 bankfull widths) are required for wood abundance.

These findings raise some important sampling issues in small streams. For example, if the purpose is to determine reference loads or targets (refer to Fox et al. 2003; Lisle 2002) that are required to meet certain thresholds that initiate forest management activities or regulatory consequences then defensible and dependable thresholds must be based on meaningful wood load estimates. Issues associated with determination of wood load estimates are often confounded by the fact that these streams are physically limited by the upper most extent of the stream at which point these streams become undefined. Similarly, in a downstream direction the heterogeneity of larger streams increases due to larger channel widths, increased stream power, variations in forest stand condition and variations in the interplay of the various wood input and output processes. Therefore, further clarity is required to adequately characterize the spatial and temporal distribution of wood in order to minimize uncertainty.

A power analysis based on a subset of data from this study along with the observed high variability of wood loads associated with the various disturbance categories or stand development stages highlights the importance of using caution in applying the findings from this study. Low power was an issue for this study due to high variability and small sample sizes. Although large differences in wood volumes and abundance were detected between some of the disturbance categories or stand development stages, the lack of observed differences in comparison of streamside clearcut harvested streams and older, undisturbed streams should be considered inconclusive. As a consequence, future studies or monitoring activities should carefully consider the findings of this study in development of future study designs to improve statistical inference. An important element in future study designs should be focused on development of meaningful biological or geomorphic measures of instream wood for small streams to ensure comparisons have a stronger ecological basis.

8.2.5 Forest Management Implications

The following provides a summary of key findings that can be used to guide riparian management and development of best management practices adjacent to small streams in the south-central British Columbia.

- Provided that emulation of natural disturbance is an overriding forest management strategy, riparian areas should be managed to preserve the dynamic, pulsed nature of wood inputs since instream wood is likely never in equilibrium with the surrounding riparian forest. In the context of forest harvesting, appropriate management practices may include retention of stream-side trees that subsequently blow over and eventually become integrated into the stream channel. This suggestion needs to be tempered against potential sediment erosion issues that may arise from exposure of mineral soil due to overturning of rootwads.

- Over successive harvest rotations (i.e. time scale ~150 years) and in absence of episodic inputs of wood it is likely wood loads will become suppressed; therefore, both the short-term and long-term implications of various riparian management strategies should considered.
- Monitoring protocols that are designed to compare existing wood loads to predefined "natural" reference loads need to recognize the inherent variability and dynamic, temporal nature of wood observed in this study. In particular, the likelihood that equilibrium wood loads do not occur completely invalidates the concept of "reference loads." Furthermore, this inherent variability of wood has important statistical implications in relation to sample sizes and reach lengths required to determine wood loads to given level of uncertainty (refer to Chapter 7).
- A common post-fire practice is to log and remove burned and dead riparian trees based on the concern that this wood could block culverts and bridges subsequently causing washouts and flooding (Young 1994; Debano et al. 1998). Such concerns are unsupported for the small streams considered in this study based on the stability of wood observed.

- Monitoring protocols to evaluate forest practices in riparian areas should not only consider the volume and number of wood but should also consider the characteristics and condition of wood such as the position and decay state of wood.

8.3 RECOMMENDATIONS FOR FURTHER RESEARCH

Several recommendations for further research follow from the work described in this thesis.

1. Limited information related to the linkage between ecosystem functions, aquatic organisms and instream wood in response to wildfire disturbances or streamside clearcut harvesting is available for small streams. While this study made progress in linking channel morphology to instream wood, more work is required to further link channel morphology to aquatic habitat. Further study is required to develop meaningful biological and geomorphic measures of instream wood from across a broader geographic area, forest stand stages and stream types to better refine our understanding about the linkages between these variables.

2. There is a need for further research and development of stratification procedures and protocols that combine traditional geomorphic stream classification systems with instream wood classification systems that better characterize the spatial arrangement of wood based on wood input, output and transport processes at various spatial and temporal scales. Improved

stratification is an important element in designing studies or monitoring activities to assess the effects of logging.

3. Detailed chronosequence studies utilizing dendrochronological data associated with various forest stand stages and types is required to further our understanding of the relation between forest stand dynamics and instream wood. This information would provide important insight into the relative role of various episodic and chronic input (e.g. catastrophic disturbances vs. chronic mortality) and output (e.g. decay vs. wood transport) processes.

4. Limited information is available regarding the effects of streamside clearcut harvesting over the long-term or over successive rotations adjacent to small streams. Given the limitations of field studies in relation to long-term phenomena such as instream wood dynamics there is a need for multiscale, long-term research programs that integrate wood recruitment model development/testing with field-based process studies. The models can help to extend the field-based results through time, and can serve as decision-support tools for natural resource managers.

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APPENDIX

APPENDIX A: PRECISION AND ACCURACY OF RAPID STREAMBED PROFILE METHOD

The rapid streambed profile (RSP) method has been identified as a being a precise and rapid alternative to more time consuming bed elevation procedure (BEP) (Stack 1989; Stack and Beschta 1989, Robison and Kaufmann 1994; Robison 1997). The RSP method defines residual pool depth as the difference in elevation or depth between a pool and its downstream riffle crest (Lisle 1987) or more simply, is the location where water would collect if the flow approaches zero (Stack and Beschta 1989). Individual and aggregate residual pool characteristics for each study reach were calculated from field measurements using thalweg depth, wetted width and overall reach slope. The thalweg depths collected longitudinally at 1 meter intervals were used to calculate residual pool depths by projecting a downward diagonal line from a downstream control point (i.e. riffle crest) until it intersects a shallower depth upstream. The residual depth is the difference between the diagonal line and the bed depth (Robison 1997). Stack (1989), Robison and Kaufmann (1994) and Robison (1997) have shown that the downward slope of the diagonal line (DLS) is related to the actual slope of the stream (SLOPE); therefore, the diagonal line can be corrected for slope using the following equation:

(2) $DLS = 0.4454 * SLOPE^{0.942}$ (Robison 1997)

This equation was developed by Robison (1997) from 31 sites with slopes ranging from 0.1-17.7% in Oregon and was considered appropriate for the streams situated within the southern British Columbia (Robison 2005, personal communication). Once the residual depths were determined after correcting for slope the longitudinal profile area (Ar_i, sagittal area) in a residual pool was calculated by multiplying the residual depths (Dr_i) by the incremental distance (DS_i) along the profile. These areas can be summed for individual pools or the entire reach.

(3) $Ar_i = (Dr_i) * (DS_i)$

Residual pool volume can then be calculated from the residual area and residual width. Robison and Beschta (1989) found that the residual width can be approximated by assuming that the cross-sectional area can be approximated by a triangle with thalweg depth and wetted width representing the height and base of the triangle. Using this assumption and simple geometry the residual width can be calculated from measured thalweg depth (Dm_i), residual depth (Dr_i), and measure wetted width (Wm_i):

(4) $Wr_i = Wm_i * Dr_i / Dm_i$

Residual volume can then be calculated using the equation for a triangle:

(5) $Vr_i = 0.5 * Wr_i * Ar_i$

Robison (1997) found strong correlation (r^2 = 0.96) between the RSP and BEP for residual pool area utilizing the DLS equation (3). This assumption was further verified based on data collected from seven streams situated within the south-central interior of British Columbia (Figure A.1) also yielding strong relation (r^2 = 0.94, $p < 0.001$) between the RSP and BEP methods. These streams are part of a long-term monitoring project being lead by Dr. Adam Wei at UBC Okanagan. Drainage areas for the comparison ranged between 7 to 30 km^2 with streambed slopes ranging between 2 to 7%.

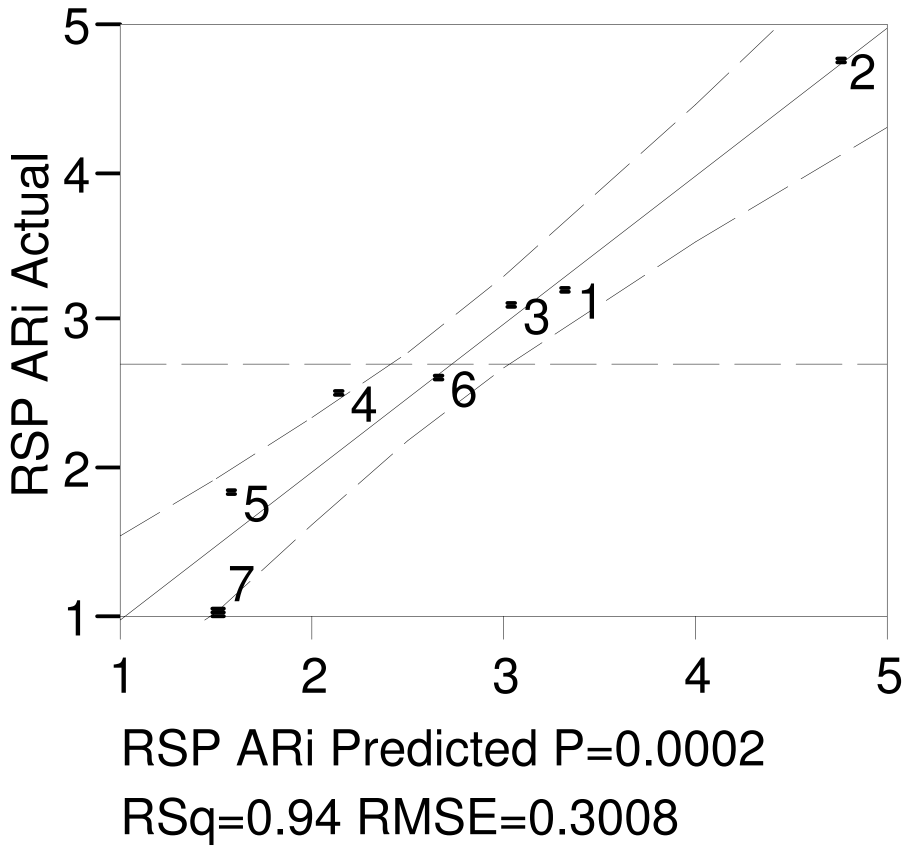

Figure A.1. Linear comparison of the rapid streambed profile (RSP) method with the more detailed bed elevation procedure (BEP) for longitudinal (sagittal) residual area. The comparison is based on seven stream reaches situated within the south-central interior of British Columbia. Ninety-five percent confidence intervals indicated by hashed lines.