POSTHARVEST WINDTHROW AND RECRUITMENT OF LARGE WOODY DEBRIS IN RIPARIAN BUFFERS

by

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Abstract

Large woody debris (LWD) is an important component of forest ecosystems and provides structural complexity to small streams. Riparian buffers are intended to provide long term supplies of LWD, but post harvest windthrow often occurs. To document the impacts of windthrow in riparian buffers and identify the components needed for small stream LWD recruitment modeling, I sampled 39 small streams at the Malcolm Knapp Research Forest (MKRF) and on Vancouver Island. I took two basic approaches. In the small stream experiment at MKRF a series of small clearcuts were harvested in 1998 in a 70 year old second growth stand. I measured LWD in 10m and 30m buffer treatments, and in the unharvested control. I added samples in mature and old-growth stands for comparison. In the second approach, I retrospectively sampled buffers that were exposed by harvesting from 0-20yrs ago on southwestern and northeastern Vancouver Island. In both studies, all logs greater than 7.5 cm diameter at mid-creek, in decay class 1 to 4 that spanned at least part of stream channel width were measured. There was no significant difference in the number of spanning and in-creek logs in 10m and 30m buffer given the short term monitoring of woody debris in the buffers. The majority of windthrown trees were still suspended above the stream channel years after a windthrow event. The height above stream was negatively correlated with log decay class and the buffer age class. The number of logs was higher in immature stands than mature stands. As the stems per hectare in riparian stands increases, so does the frequency of spanning LWD. The frequency of logs in decay classes 3 and 4 was higher in older buffers, and deciduous LWD decayed more quickly than conifers. Interestingly, the log length was found to be shorter in advance stage of decay. Key elements in a conceptual model of LWD recruitment via windthrow are the geometry of initial log position, log size, species and decay rate.

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1. Introduction

1.1 Background

Large woody debris (LWD) is an important component of forest ecosystems. It helps to structure fish habitat (Bisson *et al*. 1987), shape channels (Swanson *et al*. 1976), and trap sediments (Swanson and Lienkaemper, 1978). The transfer of LWD from streamside forests to the stream and river system creates a strong linkage between terrestrial and aquatic ecosystems (Lienkaemper and Swanson, 1987).

Unharvested riparian management areas (‘buffers’) are intended to minimize impacts of forest management activities on water quality, aquatic ecosystems and riparian community diversity (BCMOF 1995). However, 15% of cutblock boundary segments in wind exposed areas of coastal BC are partially windthrown following harvesting, and riparian buffers are particularly susceptible (e.g. Steinblum *et al*. 1984, Rollerson and McGourlick 2001). Significant progress has been made in recent years in developing empirical models to characterize windthrow probability on cutblock edges and within partial cuts (Lanquaye-Opoku and Mitchell 2005, Scott and Mitchell, 2005), but these models have not been extended to riparian buffers. For designing effective riparian prescriptions, we need to estimate both the probability of windthrow and the potential impacts of windthrow. These impacts include loss of overstory, introduction of LWD into the streams, pulse introduction of foliage and fine branch materials, loss of bank stability and exposure of sediment sources (Lewis 1998, MacDonald *et al*. 2003).

1.2 Problem statement

LWD recruitment commences with the uprooting or breakage of standing live or dead trees. In the existing LWD recruitment models, fall direction is either treated as 'random' or conditioned by the user based on 'expert' knowledge or empirically derived data. Post-windthrow tree position and suspension time is often ignored. Windthrow in newly exposed riparian buffers is often viewed as a pulse source of LWD input. However, based on initial examination of windthrow in riparian buffers, most recently windthrown logs are suspended well above the stream channel. Recruitment into the stream will take therefore place over many years. A conceptual model that more realistically captures the geometry and decay processes will provide the basis for development of an LWD recruitment module that can be run in conjunction with stand growth models, or windthrow risk models.

1.3 Thesis objectives

This thesis work takes place within the context of a larger program of studies on windthrow assessment and management lead by Dr. Mitchell. The specific objectives of this thesis project are to:

1. Sample a range of riparian buffer and stand conditions in order to document the geometry of post-harvest windthrow in riparian buffers in stands of different ages and buffers of different widths.

2. Investigate the change in condition of stream spanning LWD over time since harvest in riparian buffers.

3. Develop the framework for a process model that simulates windthrow supply of LWD to streams within riparian buffers.

1.4 Research questions

1. How do tree fall orientation and the interaction with valley and channel geometry affect the position of post-harvest windthrow origin LWD relative to the stream channel?
2. How does the position of windthrow origin LWD relative to the stream vary with log size and decay class?
3. Are there predictable trends in LWD position and log decay class with time since harvest?
4. Do these trends differ for different species?
5. How are these trends affected by stand age and buffer width?
6. What are the essential components of a process model for simulating windthrow origin LWD recruitment into streams?

1.5 Approach

The thesis starts with a review of existing knowledge on LWD, decay classification, decomposition models, recruitment models, and decay rates for local tree species. The experimental chapters focus on LWD recruitment and change in condition over time. I used two different approaches for this research. At the Malcolm Knapp Research Forest (MKRF) I documented LWD in the riparian buffers experiment in fixed buffer width treatments (10m, 30m) and the unharvested control. The riparian buffers experiment was established in 1995 by Dr. Michael Feller of the Faculty of Forestry, University of British Columbia with the harvesting in 1999. This experiment was in a 70 year old stand. To provide context for this experiment, I took a chronosequence approach and measured windthrow and woody debris in a 130 year and old growth (500+ years) stand at MKRF using the same sampling methodology.

In the second component of the thesis, I took a retrospective approach and sampled buffer strips on Vancouver Island that had been exposed on both sides for 0-5years, 6-10years, 11-15years and 16-20 years following harvesting of the adjacent timber. Both of the study areas in Vancouver Island (Bamfield and Port McNeill) were representative of wind exposed west coast forests with young mature (referred as immature stand) and older stands with numerous small streams. Using the retrospective approach enabled me to evaluate the pattern of change in LWD condition over time.

This thesis is divided into five chapters of which this introduction is the first chapter. The second chapter is the literature review. The third chapter describes the experiment at the Malcolm Knapp Research Forest. The fourth chapter describes the Vancouver Island component, and the final chapter is an integrating discussion with conclusions and recommendations for modeling, further research, and riparian management.

2. Literature review

2.1 General purpose of riparian buffers

Riparian zones are critical components of terrestrial and aquatic ecosystem and are important ecotones that influence complex interaction between terrestrial and aquatic environments (Hedman et al. 1996). A key function of a riparian buffer is to supply large woody debris (LWD) to aquatic ecosystems (Sickle and Gregory 1990, Naiman and Bilby 1998, Grizzel and Wolf 1998) and thus the goal of riparian forest management typically includes the long term supply of wood to streams (Meleason *et al*. 2002). However, a riparian buffer also provides several other key functions. It influences the stream condition like flow level (Cleverly *et al*. 2000), moderates the stream temperature (Helfield and Naiman 2001, Moore *et al*. 2005), and helps in channel and bank stability (Liquori and Jackson 2001, Simon and Collison 2002). The shade provided by riparian trees is a dominant factor maintaining cool water in many forested streams (Brown 1969). It also provides the input of organic materials like leaf litter (Gregory *et al*. 1991, Bisson and Bilby 1998) and also influences the microclimate (Brosofske *et al*. 1997). In recognition of the importance of riparian forests, the British Columbia Forest Practices Code (FPC), enacted in 1994, required the establishment of riparian reserves and riparian management zones adjacent to streams depending on stream width and the presence of fish. However, for streams with less than 1.5 m bankfull width, buffer strips are not mandatory and less protection is afforded under forest practices guidelines (Beese *et al*. 2003; Moore *et al*. 2005).

2.2 Large woody debris

2.2.1 Definition

The terms large woody debris (LWD) and coarse woody debris (CWD) are used to denote dead downed trees, but CWD also includes standing dead trees i.e. snags (Harmon *et al*. 1986, Vanderwel *et al*. 2006). In general, wood in aquatic ecosystems is referred as LWD whereas in terrestrial ecosystems it is referred to as CWD. For example, the British Columbia Ministry of Environment Land and Parks (BC MOELP 1999), distinguishes LWD, which is fallen wood that is associated with the stream, from CWD, which is larger pieces of dead and downed wood on the forest floor and horizontal logs.

The term LWD generally includes the whole tree, logs, large branches and rootwads, but there are also more precise definitions of LWD. The MOELP has defined LWD as "pieces of dead wood, having a diameter of 10 cm or larger over a minimum 2 m length, that intrude into the stream channel". The BC Ministry of Forests (BC MOF) defined LWD as "a large tree part, conventionally a piece greater than 10 cm in diameter and 1 m in length." In contrast, the Governor's Salmon Recovery Office, Washington State defines LWD as "coniferous or deciduous logs, limbs or root wads, twelve inches or larger in diameter, that intrude into a stream channel or nearby." Among scientific studies, the minimum piece size varies widely. For example, the minimum diameters range from 7.5-15cm in western North American studies and from 2.5-7.5cm elsewhere (Harmon *et al*. 1986). Some ecologists (e.g. Christensen 1977) make no distinction between coarse woody debris and fine woody debris. Most studies define LWD based on the diameter whereas others use both diameter and length. The studies using diameter to define LWD used a minimum size specification of greater or equal to 10cm diameter (Wallace *et al*. 2001). The studies that include both diameter and length, used lengths of at least 1 m (Murphy & Koski 1989, Fausch & Northcote 1992, Wei 2004, Kreutzweiser *et al*. 2005, Opperman 2005, Fetherston *et al*. 1995, Lamberti & Gregory 1996, Gurnell *et al*. 2002), 1.5 m (Lienkaemper & Swanson 1987), 1-2 m (Long 1987, Ursitt 1990, Bilby & Ward 1989), or 3 m (McHenery *et al*. 1998). Some authors even use variable lengths. Martin and Benda (2001) used 1.5 m or longer in channel less than 5m wide and 3m and longer in wider channels. Finally, some researchers counted only logs as LWD (e.g. Lienkaemper and Swanson 1987, Martin and Benda 2001) while the more general definition of LWD include large branches and rootwads as well. For this research I used a minimum size of 7.5cm diameter at midcreek, with no minimum length.

2.2.2 Source of LWD

The main source of LWD in small streams is from the adjacent riparian forest (Naiman and Bilby 1998, Grizzel and Wolff 1998). Riparian buffers are particular susceptible to windthrow following harvesting (Rollerstone and Mc Gourlick 2001). For some streams, windthrow is the dominant input process from the riparian buffer (Lienkaemper and Swanson 1987). However tree falls can result from several processes including bank erosion, mass failure of adjacent side slopes, wildfire (Wei 2005 a), bank undercutting during high flow events (Johnson *et al*. 2000), competition or pest induced mortality, snow loads, and ice loads (Sampson and Wurtz 1994, Oliver and Larson 1990). Abiotic factors like flooding, mineral deficiencies and drought may make tree more susceptible to biotic stresses such as insect infestation and disease (Kozlowski *et al*. 1991). The recruitment of standing live tree into streams due to windthrow occurs when either the whole tree is uprooted, or a part of tree is broken during peak wind events. Windthrow is often directional, reflecting dominance of particular local wind patterns (e.g. Scott and Mitchell, 2005)

2.3 Decay classification

2.3.1 Review of snag classification

Both standing trees and downed logs are subject to decay processes and these processes often start prior to tree death. Since the state of decay affects the structural condition and habitat value of the tree or log, there are various decay classification systems. A snag is a standing dead tree from which the leaves and most of the limbs have fallen (Thomas 1979). The various snag classifications are summarized in Table 2.1 by location of study, number of decay classes, species and attributes considered.

Table 2.1 Decay classification for Snags

S.N	Author and Year	Location	Species	No of class	Attributes considered
1	Cline *et al*. (1980) from Thomas *et al*.* (1976)	Western Oregon	Douglas-fir	5	Limbs & branches, top, bark, sap wood and heart wood
2	Raphael and White(1984)	Sierra Nevada	Jeffrey pine, white fir, lodgepole pine,aspen, red fir, mountain hemlock	6	Condition of tree, needles, twigs, branches
3	Raphael and Morrison (1987) from 2	Sierra Nevada	Jeffrey pine, white fir, red fir, lodgepole pine, mountain hemlock, aspen	5	needles, twigs, branches
4	Morrison and Raphael (1993) from 3	Sierra Nevada	Jeffrey pine, white fir, red fir, lodgepole pine, mountain hemlock	5	needles, twigs, branches
5	Ganey (1998) from 2	Northern Arizona	Ponderosa pine and mixed conifer	5	needles, twigs, branches
6	Everret *et al*. (1999) from 1	Washington	Douglas fir, ponderosa pine, sub alpine fir, Engelmann spruce	5	Limbs & branches, top, bark, sap wood and heart wood
7	Enrong *et al*. (2006)			5	Leaves, bark, crown, branch & twigs, bole, indirect measure
8	Vanderwel *et al*. (2006)	Ontario	White/ red pine, red oak, white birch, spruce, balsam fir, red maple, aspen	5	Top, bark, branches, height
9	Hennon *et al*. (1990)	Southeast Alaska	Yelow Cedar	6	Foliage, twigs, Primary and secondary branches

*Original paper not found. Cited in other papers

Many authors classify snags according to 5 stages of decay (Cline *et al.* 1980, Raphael and White 1984, Raphael and Morrison 1987, Ganey 1999, Morrison and Raphael 1993, Everret *et* *al.* 1999, Enrong *et al*. 2006, Vanderwel *et al.* 2006), however, there is considerable variability in how these classes are defined. Cline *et al.* (1980) used a snag classification system by Thomas *et al.* (1976) for Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) forests in Oregon, where stages 1 and 2 include hard snags and 3 to 5 were soft snags. Approximate ages were assigned to each stage of decay, for example 0-6yrs, 7-18 yrs, 19-50 yrs, 51-125 yrs, and 126 yrs & older for decay stages 1 through 5 respectively. The parameters used for classifying snags into decay stages were limbs and branches, top of tree, percent of bark remaining, sapwood and heartwood condition. Everett *et al.* (1999) used the same snag classification for their work on snag dynamics in a chronosequence of wildfires in Cascade range in Washington state, but found that thick barked species like Douglas-fir and ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) took 15-25 years to reach stage 3 decay, while thin barked species took 65 years to reach the same stage of deterioration. Raphael and White (1984) added a 6th class because they included live trees in the first stage. These authors define classes based upon tree condition, i.e. live or dead, needles, twigs and branches. Stages 5 and 6 were soft snags with substantial wood rot. This classification system minus the live tree class was used by Raphael and Morrison (1987), Morrison and Raphael (1993) in California and by Ganey (1998) for ponderosa pine and mixed conifers in northern Arizona.

2.3.2 Review of large woody debris classification.

The number of LWD/CWD classes in various systems ranges from 3-8 (Appendix 3). Classifications with 5 grades of log decay are the most common, though Grette (1985), Murphy and Koski (1989), Lee *et al.* (1997) and Hyatt and Naiman (2001), use seven grades, and McCullough (1948), Soderstrom (1988, 1989), and Næsset (1999) use eight grades. There are also studies with only three grades in New Zealand (Stewart and Burrows 1994) and Ontario

(Pedlar *et al.* 2002). In BC, Feller recommended four decay classes (Feller 2003). The 5 class decay classification by Fogel *et al.* (unpublished) is used extensively for Douglas-fir (Sollins 1982, Spies *et al.* 1988, Sollins *et al.* 1987); western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (Graham and Cromack 1982, Christy and Mack 1984) in the Pacific Northwest and in Alaska (Robinson and Beschta 1990); for Sitka spruce (*Picea sitchensis* (Bong.) Carriére) and red alder (*Alnus rubra* Bong.) in Alaska (Robinson and Beschta 1990). Murphy and Koski 1989 used 7 grades of log decay adapted from Grette 1985 for western hemlock and sitka spruce in Alaska. Seven class decay classification was also used by Lee *et al.* 1997 for aspen dominated boreal forest in Alberta and by Hyatt and Naiman 2001 for sitka spruce, Douglas fir, western hemlock and Black cottonwood (*Populus balsamifera* L. ssp. *trichocarpa* (Torr. & A. Gray ex Hook.) Brayshaw.) in Washington.

As with LWD/CWD, the attributes used to assign snags to classes, and the condition of these attributes, varies among classification systems. The common attributes that were used to assign decay class to logs were: bark condition (bark intact or absent); structural integrity (wood sound, sapwood rotten, or heartwood rotten); and branch condition (all twigs present, large branches present, or absent). Invading roots were sometimes used for decay class description (Sollins 1982, Christy and Mack 1984, Maser and Trappe 1984, Idol *et al.* 2001, Enrong *et al.* 2006). Presence of vegetation on logs was another feature used to assign logs to a decay class (Sollins 1982, Christy and Mack 1984, Lee *et al.* 1997, Idol *et al.* 2007, Siitonen *et al*. 2000, Vanderwel *et al.* 2006, Enrong *et al.* 2006, Spies *et al.* 1988, Takahashi *et al.* 2000, Hofgaard 1993, Næsset 1999)

The color of the wood was also considered in some decay classifications (e.g. Maser and Trappe 1984, Robinson and Beschta 1990, Pyle and Brown 1999, Feller 2003, Enrong *et al.* 2006). Some of the decay classifications include the portion of tree on the ground (e.g. trees elevated on supported points, sagging, or on ground; Maser and Trappe 1984, Christy and Mack 1984, Sollins *et al.* 1987, Enrong *et al.* 2006). The texture of log, e.g. intact, smooth, abraded or vesicular, was also considered by some authors (Maser and Trappe 1984, Robinson and Beschta 1990). Recently downed trees typically constitute the first decay class (McCullough 1948, Sollins 1982, Christy and Mack 1984, Sollins *et al.* 1987, Lindenmayer *et al.* 1999, Siitonen *et al.* 2000, Jonsson 2000, Feller 2003).

The majority of five class decay classification system are modified forms of Fogel *et al's.*1973 classification. There are a few LWD classifications based only on structural integrity and soundness of sapwood and heart wood (e.g. Delong *et al.* 2005, Newbery *et al.* 2004). But case-hardening as a result of forest fire was not considered in any of the classifications even though with case-hardening the nature of the decay pattern changes. Wei (2004) used the same decay classification (modified from 5 classes system by Robison and Beschta 1990) for his work on quantifying the difference of in stream woody debris between harvesting and wildfire disturbance in Interior BC.

The path of standing live trees to dead downed wood is well illustrated by Maser *et al.* (1979; Fig 2.1). A healthy standing tree can come down only if it's blown down by the wind, broken by snow or ice, or cut down. Whereas the change in status of standing live trees to standing dead may be due to various factors like suppression and competition, insect pest attack, fire and others. The decay class of down trees is depended on the condition of the preceding live tree or snag. If a tree is healthy or recently dead and comes down then it will be in the first decay class

(Table 2.2). But if the snag loses its branches and bark and then comes down then it may enter as logs in the second decay class. A snag in decay class 5-6 stage may enter as logs in decay class 3.

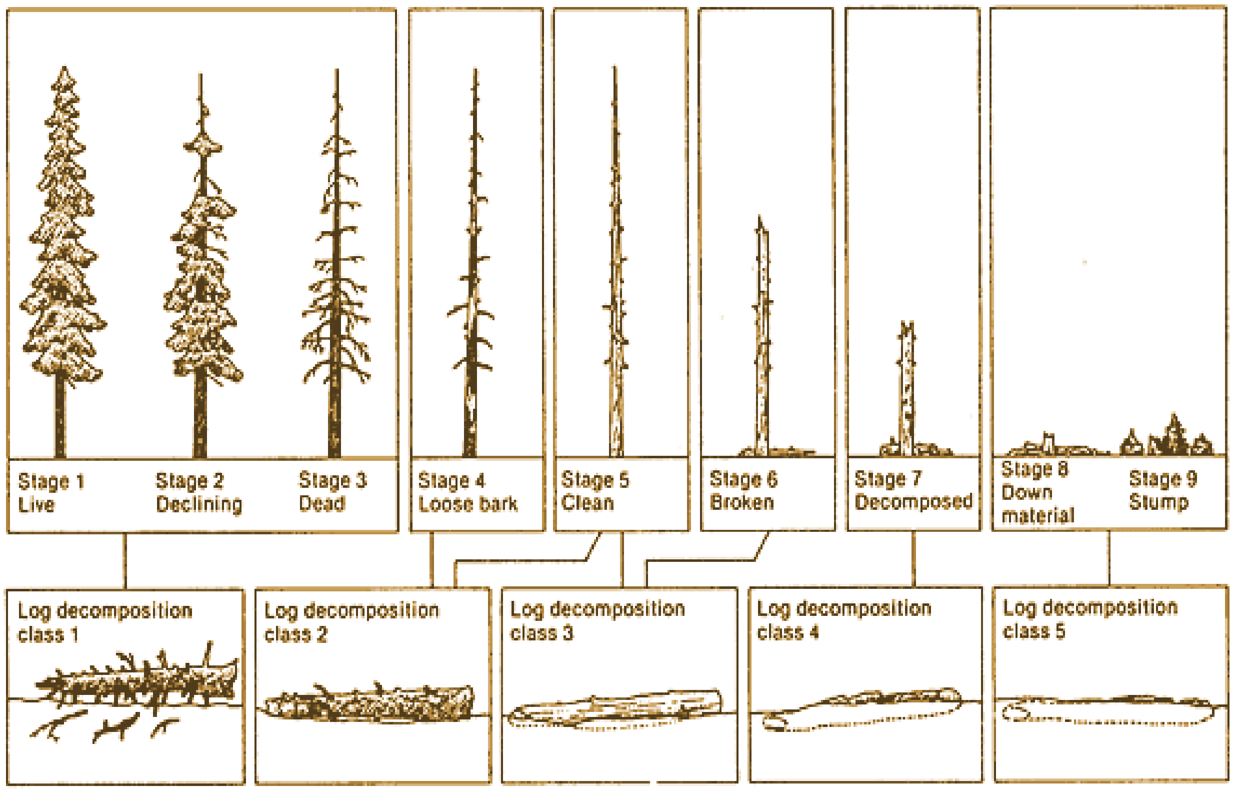


Fig 2.1 Translations of standing live trees and snag into log decay classes. (Maser *et al*. 1979)

The LWD decay classification we are using for our research is the 5 decay class system (2.2), which is the most extensively used system in the U.S Pacific Northwest. However, I have included recently felled trees in the first decay class. For standing trees, I used the 9 stage classification system (Fig 2.1) used by BC ministry of Forests.

Table 2.2 Classification of LWD decay classes (Bartels *et al*. 1985, MOFR 2007)

	Class 1	**Class 2**	**Class 3**	**Class 4**	**Class 5**
Bark	Intact	Intact	Trace	Absent	Absent
Twigs	Present	Absent	Absent	Absent	Absent
Texture	Intact	Intact to partly soft	Hard large pieces	Small, soft blocky pieces	Soft and powdery
Shape	Round	Round	Round	Round to oval	Oval
Color of Wood	Original color	Original color	Original to faded	Light brown to reddish brown	Red brown to dark brown
Portion of tree on ground	Tree elevated on support points	Tree elevated on support points but sagging slightly	Tree sagging near ground	All of tree on ground	All of tree on ground
Invading roots	None	None	In sapwood	In heartwood	In heartwood

Table 2.3 Snag condition translated into log decomposition class (Maser *et al*. 1979)

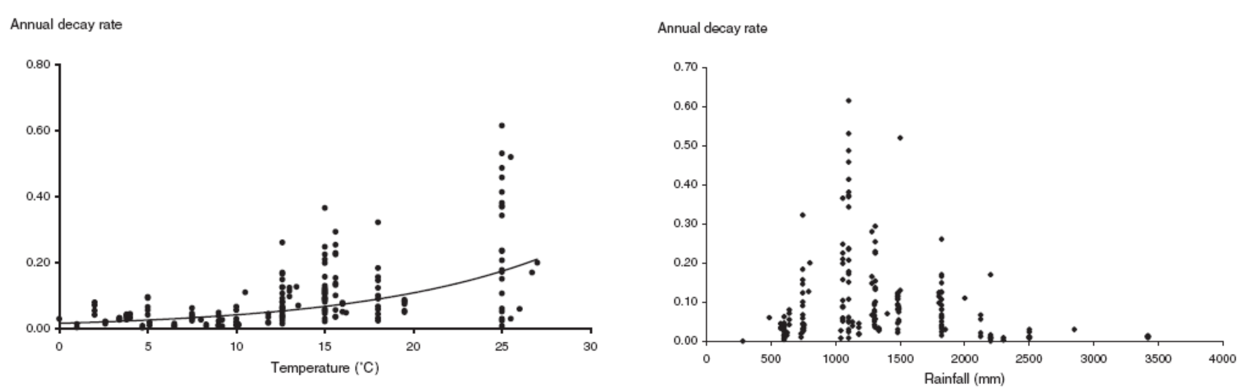
Snag stage	**Snag condition**	**Log class**
1-3	Hard snag	1
4-5	Hard snag	2
5-6	Soft Snag	3
7	Soft snag, 70%+ soft sapwood	4

2.4 Factors affecting the rate of decay

Decomposition is a complex phenomenon which includes different processes like respiration, biological transformation (Swift 1973), leaching (Mattson and Swank 1984), and fragmentation (Harmon *et al*. 1986). The factors that affect the rate of decomposition of LWD include climate, tree species (the chemical content), the size of the debris (diameter, length), position (suspended, on ground, submerged, and buried), decomposition process (fragmentation, leaching, respiration), channel morphology, flood intensity, and riparian forest composition (Thomas *et al*.

1979; Harmon *et al* 1986; Naiman *et al*. 2002). The main process behind decomposition is the loss of organic matter through microbial respiration (Chambers *et al*. 2001, Mackensen *et al*. 2003), which contributes 76% to the loss of C from dead wood. The activity of microbes depends upon temperature, moisture and substrate quality. The prime determinant of the decomposition is hard to say (Swift *et al*. 1979, Brown *et al*. 1996). LWD surface area affects the rate of decay as microbial decomposition occurs from the surface inwards (Naiman *et al*. 2002).

Mackensen *et al*. (2003) found a strong relationship between mean annual temperature and decay rates with great variation at higher temperature (Fig 2.2a). Though decomposition processes are positively related to moisture content, the decomposition is retarded in saturated wood. For example, Progar *et al*. (2000), found that respiration from Douglas-fir logs declined at higher moisture content. Decay rates were higher at annual precipitation of about 1200-1300mm beyond which decay rates are uniformly lower (Mackensen *et al*. 2003; Fig 2.2b).



(a) (b)

Fig 2.2 (a) Relationship between mean annual temperature and annual decay rate constant of CWD. (b) Relationship between mean annual rainfall (mm) and annual decay rate constant of CWD (from Mackensen *et al*. 2003)

The relationship between log diameter and rate of decay has been the focus of many studies. Erickson *et al*. (1985) showed positive correlation between these parameters for Douglas–fir, whereas other studies (e.g. Graham and Cromack 1982, Foster and Lang (1982), Johnson and Green (1991)) did not show this correlation. Mackensen *et al*. (2003) found that the decomposition rate was inversely related to log diameter (Fig 2.3). Pieces with low surface area to volume ratios decay more slowly (Bisson *et al*. 1987), which is the case in large diameter logs (Harmon *et al*. 1986). Furthermore, heartwood decomposes more slowly than sapwood and represents a larger proportion of diameter in bigger logs (Harmon *et al*. 1995).

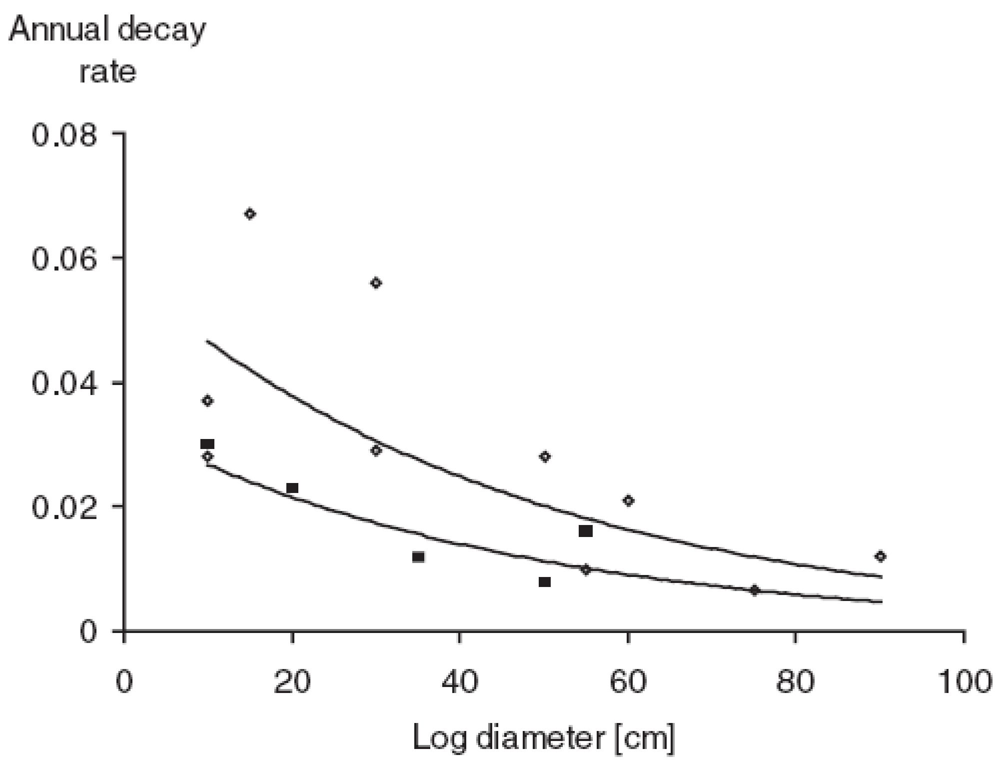


Fig 2.3 Relation between diameter and annual decay rate for *Pseudotsuga menziesii* and *Tsuga heterophylla* in north western USA. Data from Grier (1978), Graham and Cromack (1982), Sollins (1982) (estimated mean), Erickson *et al*. (1985), Means *et al*. (1985), Edmonds *et al*. (1986) (mean surface samples). Sollins *et al*. (1987), Spies *et al*. (1988) and Stone *et al*. (1998). ◊ =*P. menziesii*, $y=0.0574e^{-0.0209x}$; ■=*T. heterophylla*, $y=0.0332e^{-0.0216x}$. (Mackensen *et al*. 2003)

The rate of decomposition also depends upon the chemical constituents of the wood such as lignins, cellulose and hemicelluloses, and extractives. High lignin content lowers the decay rate (Melillo *et al*. 1983). The inner bark decomposes more rapidly compared with other wood components as it is rich in sugars (Harmon *et al*. 1986).

2.5 Decomposition models

For characterizing the longevity of logs in ecosystems and the time that a log is able to support its own weight, it is useful to have mathematical models of the decomposition process. Models proposed for leaf decomposition have been used for CWD decomposition (Harmon *et al*. 1986). Wieder and Lang (1982) concluded that single exponential and double exponential models are realistic for litter decomposition and Harmon *et al*. (1986) suggest that these models apply to CWD as well. Other models used for decomposition are the linear model and the general model. The single exponential model (Jenny *et al*. 1949; Olson 1963) has been widely used to estimate rates of litter decomposition in different parts of world and is also extensively used for coarse woody debris decomposition (Table 2.4 and Appendix 4), and for decomposition of in-creek large woody debris (Table 2.7).

Table 2.4 Decomposition Models

Model	Expression	References
Single exponential model	$X = X_0 e^{-kt}$	**1,2,3,4,5,6,7,8,9$_{a,c}$10,11,12,13,14,15,16, 18,19,20,21,22,23,24,25,26,27,28,29,30,31,32**
Multiple exponential model	$X = X_{0,1}e^{-k_1 t} + X_{0,2}e^{-k_2 t} + X_{0,3}e^{-k_3 t}$	**16,17**
Lag time model	$X = 1-(1-\exp[-kt])^N$	**9$_b$,**
Linear model	$X = X_0 - kt$	**7,14**
General model	$\Delta X / \Delta t = I(t) - kX$ *	**20**

X is proportion of initial mass, density or volumeX_0 at time t. X_{1}-$_3$ are partitioned parameters such as bark, sapwood, heartwood. N is a lag time constant, k is decay coefficient. * $\Delta X / \Delta t$ is rate of change of material I(t) is rate of input X is amount of material in compartment.

(1) Alban and Pastor 1993. (2). Busse 1994 (3). Edmonds and Eglitis 1989 (4) Erickson *et al*. 1985 (5) Fahey 1983 (6) Foster and Lang 1982 (7) Graham and Cromack 1982 (8) Grier 1978 (9) Harmon *et al*. 1986, 1987, 2000 (10) Jenny *et al*. 1948 (11) Johnson and Greene 1991 (12) Krankina *et al*. 1999 (13) Laiho and Prescott 1999 (14) Lambert *et al*. 1980 (15)MacMillan 1988 (16) Means *et al*. 1985, 1992 (17) Minderman 1968 . (18) Næsset 1999 (19) Olson 1963 (20) Sollins 1982 (21) Sollins *et al*. 1987 (22) Spies *et al*. 1988 (23) Stone *et al*. 1998 (24) Tyrrell and Crow 1994 (25) Murphy and Koski 1989 (26) Bilby *et al*.. 1999 (27) Hyatt and Naiman 2001 (28) Golladay and Webster 1988) (29) Melillo *et al*. 1983 (30) Johnson and Greene 1991 (31) Chen *et al*. 2005 (32) Jones and Daniels (2008).

The single exponential model is expressed as $X = X_0 e^{-kt}$. This model is consistent with the assumption that the material is homogenous and that decay is proportional to the amount of material remaining (Harmon *et al*. 1986), where X_0 is the initial quantity of material, X is the amount left at time t, and k is the decay constant.

Minderman 1968 came up with the idea of a double exponential model in order to reflect the fact that substrates are not homogeneous and decay at different rates. Means *et al*. (1985, 1992) expanded the double exponential model into a multiple exponential ($X = X_{0,1}e^{-k_1 t} + X_{0,2}e^{-k_2 t} + X_{0,3}e^{-k_3 t}$) and used it for Douglas fir boles. Harmon *et al*. (1986) stated that a multiple exponential model would be useful for understanding the contribution of bark, sapwood, heartwood to overall decay.

The above models considered loss of mass via respiration and leaching but mass can also be lost via fragmentation (Lambert *et al*. 1980, Sollins 1982). Hence, Harmon *et al*. (1986) came up with the idea of dividing the decay rate constant k into k_m and k_f where k_m stands for decay constant for mineralization losses (i.e. respiration and leaching) and k_f for decay constant for losses by fragmentation. Since there is a lag time before fragmentation, Harmon (1987) used a lag time model $X = 1-(1-\exp[-k_f t])^N$, where k_f is fragmentation rate constant and N is the lag time constant.

2.6 Decay rate of species

For determining the longevity of downed logs on ground or in stream, it is necessary to know the decay rate of the species. Decay rates can be categorized into the fragmentation rate and the mineralization rate (Harmon *et al*. 1986). Mineralization rate includes change in wood density by respiration and leaching and fragmentation rate is change in wood density due to mechanical fragmentation of wood. These processes will commence at different times and occur at different rates depending on a number of factors.

2.6.1 For snags

The time between tree death and beginning of fragmentation depends upon species, size, type of mortality and microclimate (Harmon *et al*. 1986). As size increases the lag time also increases (Cline *et al*. 1980). Snags decompose more slowly than downed trees (Johnson and Greene 1991). Snags have lower moisture content and reduced activity of decay organisms than downed wood positioned near or in contact with the ground (Harmon *et al*. 1986, Johnson and Greene 1991). Interestingly, the optimal moisture content for decay processes is rather narrow at 25% to 35% (Rayner and Todd 1979). Decomposition of standing boles is more rapid in more humid habitats (Sollins 1982), but is slower in saturated habitats (Murphy and Koski 1989, Bilby *et al*. 1999, Hyatt and Naiman 2001).

Table 2.5 Decay rate constant of snags (k_f and k_m)

Species	DBH	Lag time	Decay constant/year	References
		Snag bole fragmentation (k_f)		
Picea engelmannii	7.5-24	10	0.015	Mielke 1950*
Picea engelmannii	25-39	10	0.012	Mielke 1950*
Picea engelmannii	>40	10	0.009	Mielke 1950*
Pinus contorta	7.5-30	2	0.089	Bull 1983*
Pinus contorta	<25	2	0.318	Bull 1983*
Pinus ponderosa	<25	3	0.283	Bull 1983*
Pinus ponderosa	25-49	3	0.113	Bull 1983*
Pinus ponderosa	>50	5	0.161	Bull 1983*
Pseudotsuga menziesii	8-18	4	0.354	Cline *et al*. 1980
Pseudotsuga menziesii	29-31	6	0.109	Cline *et al*. 1980
Pseudotsuga menziesii	32-46	11	0.033	Cline *et al*. 1980
Pseudotsuga menziesii	47-71	17	0.055	Cline *et al*. 1980
Pseudotsuga menziesii	<40	<5	0.026	Graham 1982*
Pseudotsuga menziesii	>65	<6	0.014	Graham 1982*
Tsuga heterophylla	>25	<2	0.067	Graham 1982*
		Snag bole mineralization (k_m)		
Pseudotsuga menziesii	<40		0.027	Graham 1982*
Pseudotsuga menziesii	40-65		0.013	Graham 1982*
Pseudotsuga menziesii	>65		0.003	Graham 1982*
Tsuga canadensiis	5-15		0.04**	Harmon 1982
Tsuga heterophylla	<25		0.017	Graham 1982*
Tsuga heterophylla	>25		0.016	Graham 1982*

***cited in Harmon *et al*. 1986**
**** cause of death by fire**

Decomposition rates of regional tree species vary from study to study (Table 2.5). For example, the bole fragmentation rates for snags range from 0.354 for small diameter Douglas-fir (Table 2.5; Cline *et al*. 1980), through 0.318 for lodgepole pine (*Pinus contorta* Douglas ex Loudon) <25cm dbh (Table 2.5; Bull 1983). The slowest rate reported was for Engelmann spruce (0.009/year) >40cm dbh (Table 2.5; Mielke 1950). Bole mineralization rates are lower than fragmentation rates. For large diameter Douglas-fir; Graham (1982) reported a rate of 0.003, and rates as low as 0.006 have been reported for lodgepole pine (Fahey 1983).

2.6.2 For logs

The decay rate constant of downed logs estimated by different studies is given in Appendix 4. The decay constants are estimated from logs on the ground using decomposition models (Table 2.4). The decay constant of Douglas-fir (on the ground) ranges from 0.007/year (Appendix 4; Means *et al*. 1985, 1982) to 0.067/year (Appendix 4; Stone *et al*. 1998) in the U.S Pacific North West. The in-creek decomposition rate constant of the same species is found to be 0.026/year (Table 2.7; Bibly *et al*. 1999). However Kimmey and Furniss (1943) reported the decay rate of Douglas-fir killed by fire to be 0.8-1.8 per year which is higher than the decay rate constant of downed Douglas-fir on and in streams. See Table 2.7 for decomposition rate constant of in stream woody debris. The decay rate constant for western hemlock also ranges from 0.01/year to 0.023/year (Appendix 4; Graham and Cromack 1982) where as the decomposition rate constant ranges from 0.01/year (Table 2.7; Murphy and Koski 1989) to 0.031/year (Table 2.7; Bilby *et al*. 1999) in-creek. However, this difference may be due to the study location, one was conducted in Alaska whereas the latter on in western Washington (Appendix 4). Anderson *et al*. (1978) found that western redcedar decomposed most slowly, followed by Douglas-fir and western hemlock, while red alder decayed fastest. Using the single exponential model, studies in the coastal regions of the U.S Pacific Northwest indicate that the woody debris remains in the stream for 70-100 years, with some pieces lasting from centuries to millennia (Naiman *et al*. 2002).

The decomposition of woody debris in the stream environment is complex. (Harmon *et al*. 1986). The rates of decomposition in coastal stream ecosystems range from 1 to 3% per year (Benda and Sias 2003) whereas the estimated decay rate of old growth conifer debris was 1 % per year but there were differences between species (Grette 1985). The decomposition rate constants of in-creek woody debris summarized in Table 2.7 ranged from 0.01- 1.20 per year. Variations in decomposition rates are highly dependent on species, size, wood chemistry, and degree of submersion (Scherer 2004). Wood that is constantly submersed has a much slower decay rate than those pieces that are repeatedly wetted and dried (Bilby *et al* 1999). Stone *et al*. (1998) demonstrated the effect of decay class and piece size on the decay constant (k). Larger pieces decayed more slowly, so with increasing diameter and length, the value of k decreased.

Table 2.6 Decay constants (Source: Densmore *et al*. 2005)

Species	Decay constant (k/yr)
Interior and Coastal Douglas-fir	0.02
Sitka and white spruce	0.02
Interior and Coastal western hemlock	0.03
Lodgepole pine	0.04
Western redcedar	0.01

Table 2.7 Decay constant for in-creek woody debris

Species	Location	Decay constant per year	Decay model	Stream order	References
Picea mariana	Eastern Quebec	0.35	Single exponential	1st	Melillo *et al*. 1983
Picea sitchensis	Olympic mountains	0.03	Single exponential	>=5th	Hyatt and Naiman 2001
Picea sitchensis	Southeast Alaska	0.01-0.03	Single exponential	2nd -5th	Murphy and Koski 1989
Pseudotsuga menziesii	Western Washington	0.026	Single exponential	2nd -5th	Murphy and Koski 1989
Poplus tremuloides	Eastern Quebec	0.4	Single exponential	1st	Melillo *et al*. 1983
Thuja plicata	Western Washington	0.026	Single exponential	3rd	Bilby *et al*. 1999
Thuja plicata	Olympic Mountains	0.03	Single exponential	>=5th	Hyatt and Naiman 2001
Tsuga heterophylla	Southeast Alaska	0.01-0.03	Single exponential	2nd-5th	Murphy and Koski 1989
Tsuga heterophylla	Western Washington	0.031	Single exponential	3rd	Bilby *et al*. 1999

The default decay rate constants for each species in the BC Ministry of forest TIPSY stand level model is given in Table 2.6, where the slowest decay rate constant is for western redcedar (0.01/year) and highest for lodgepole pine (0.04/year) (Densmore *et al*. 2005). Constants were independent of piece size or decay class.

2.6.3 Effect of suspension height on decay

There is not much research on decomposition rates for logs suspended above the ground. In one of the studies done by Erickson *et al*. (1985), the decay coefficient was estimated for 2 diameter classes and 2 vertical locations (on ground and above ground) for 4 different ecosystems. The effects of diameter and location were signification for Douglas-fir ecosystems only. In general the decay coefficients were higher for on ground location (Table 2.8). In western hemlock ecosystems the k value for larger diameter is greater than small diameter class.

Table 2.8 Decay rate constant by diameter class and vertical position for 2 diameter classes (1-2 and 8-12 cm) and 2 vertical location (on and >20cm above the soil) Source: Erickson *et al*. 1985

Ecosystem	Diameter class[1]	Vertical position[2]	Decay coefficient
Western Hemlock	Medium	A	0.024
		O	0.036
	Small	A	0.010
		O	0.010
Douglas-fir	Medium	A	0.016
		O	0.037
	Small	A	0.004
		O	0.011
Pacific silver fir	Medium	A	0.009
		O	0.009
	Small	A	0.002
		O	0.003
Ponderosa pine	Medium	A	0.013
		O	0.012
	Small	A	0.005
		O	0.009

[1]Log diameter class: Medium (8-12cm), Small (1-2cm) [2]Log vertical positions: Above (A), on ground (O)

2.7 LWD recruitment models

As LWD plays a vital role in the production and preservation of riparian and aquatic habitat (Beechie and Sibley 1997), understanding recruitment and in-creek dynamics in the riparian and aquatic environment is essential for designing effective riparian management strategies. LWD recruitment models include AQUAWOOD (Wei 2005 b), The Riparian Aquatic Interaction Simulator (RAIS) (Welty *et al*. 2002), STREAMWOOD (Meleason 2001), and CWD (Bragg *et al*. 2000).

AQUAWOOD is an LWD recruitment and in-stream process model linked with the FORECAST ecosystem model (Wei 2005 b). RAIS is a quantitative model of wood recruitment and stream shading linked with a forest growth and yield model (Welty *et al*. 2002). STREAMWOOD is an individual tree based stochastic model (Meleason 2001). CWD is a riparian LWD recruitment simulator which takes the dead tree output provided by the Forest Vegetation simulator as the input and processes the dead trees and gives the LWD recruitment in-stream as a final output (Bragg *et al*. 2000). A detailed comparison of these models is given in Appendix 5. Three of the models (RAIS, STREAMWOOD, and CWD) were developed for the U.S Pacific Northwest region whereas AQUAWOOD was developed for the central interior of BC.

All these recruitment models have two sub models and the output of the first model is input for the second model. The second model is the wood model whereas the first model is for calculating the mortality of the trees in stands (Fig 2.4). The process of recruitment includes competition mortality (all models), windthrow (RAIS model), upstream import (AQUAWOOD and STREAMWOOD model) and bank erosion (AQUAWOOD). Only RAIS directly addresses windthrow. It does this by allowing the user to specify rate of windthrow as a fraction of live trees per year. While all of these models have considered the depletion rate of wood once it is in-stream, none of these models addresses the time that it takes suspended spanning logs to enter the stream channel, or their condition when they enter the channel.

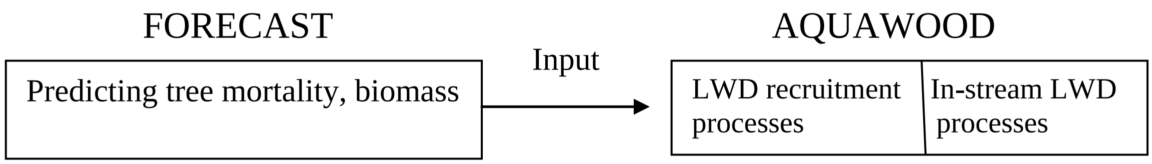


Fig 2.4 Linkage of AQUAWOOD with FORECAST (Wei 2005 b)

In order to address this knowledge gap, it is necessary to document the geometry and condition of spanning LWD, and how this changes with time since harvest. This information can then be used to build a conceptual model for recruitment of spanning LWD, to examine the appropriate functional form for model components such as log decay rates, and to estimate the rates for parameters such as the decay rate within these functions.

3. Postharvest windthrow and recruitment of LWD in the riparian buffers experiment at the Malcolm Knapp Research Forest.

3.1 Introduction

Changes in forest practices regulations in British Columbia and the northwest United States in the past two decades have lead to greater protection of small streams during timber harvesting. Forest policy in British Columbia includes the mandatory retention of buffer strips along larger stream channels with fish populations (Wang *et al*. 2002). The linkage between LWD recruitment from adjacent forests and the availability of fish habitat within the stream channel has been well established in 30yrs of research in the Pacific Northwest (Bisson *et al*. 1987). For small streams, the recruitment of woody debris is dependent on the adjacent buffer strips. Buffer strips exposed by harvesting are susceptible to windthrow (Rollerson and McGourlick 2001, Liquori 2006). The process by which this windthrow enters the channel is not well understood or modelled. Windthrow is not considered in any of the existing LWD recruitment models except RAIS by Welty *et al*. (2002), but this model assumes immediate recruitment of windthrown trees into the stream channel.

The objectives of this study were: 1) to sample a range of riparian buffer and stand conditions in order to document the geometry of post-harvest windthrow in riparian buffers. 2) to gather observations to enable development of a framework for a process model that simulates windthrow supply of LWD to streams within riparian buffers.

The following hypotheses were tested: i) the majority of windthrown trees span the creek, therefore LWD recruitment in stream does not initiate immediately after a windthrow event; ii) height above creek of spanning LWD is a function of tree point of germination, valley form, and log decay class; iii) the number of spanning trees is greater in narrow buffer width; iv) the abundance of LWD is less in older and mature stands than in immature stands, while the mid creek diameter is larger in mature stands.

3.2 Methods

3.2.1 Study area

The small streams riparian buffers experiment was established by Dr. Michael Feller at the UBC Malcolm Knapp Research Forest (MKRF) (Feller and Sanders 1999), which is located in the foot hills of the Coast Mountains, approximately 60km east of Vancouver, British Columbia. This research forest is bordered on the north and east by Golden Ears Provincial Park, on the northwest by Pitt Lake, and on the south by developed urban land. The forest lies in the Submontane (10 to 500m elevation) very Wet Maritime Coastal Western Hemlock biogeoclimatic variant (CWHvm); influenced by a prehumid cool mesothermal climate (Kiffney *et al*. 2002; De Groot *et al*. 2007). The climate is maritime and characterized by dry, warm summers and wet, cool winters. Total precipitation ranges from about 2200 mm per year at southern end to 3000 mm per year at northern end of the forest. Snow falls occasionally owing to low elevation (120-450m). Soils are shallow and composed of glacial till and some glacio-marine deposits (Feller and Kimmins 1979). The topography varies from flat to hilly and gently rolling, with some bedrock knolls.

The dominant forest tree species that characterize the maritime subzones of CWH are coniferous and include: western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), amabilis fir (*Abies amabilis* (Douglas ex Louden) Douglas ex Forbes), western redcedar (*Thuja plicata* Donn ex D.Don), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Sitka spruce (*Picea sitchensis* (Bong.)

Carriére) and yellow cedar (*Chamaecyparis nootkatensis* D.Don). Deciduous tree species including paper birch (*Betula papyrifera* Marsh.), red alder (*Alnus rubra* Bong.), and big-leaf maple (*Acer macrophyllum* Pursh) are frequent in open spaces (Feller *et al*. 2000).

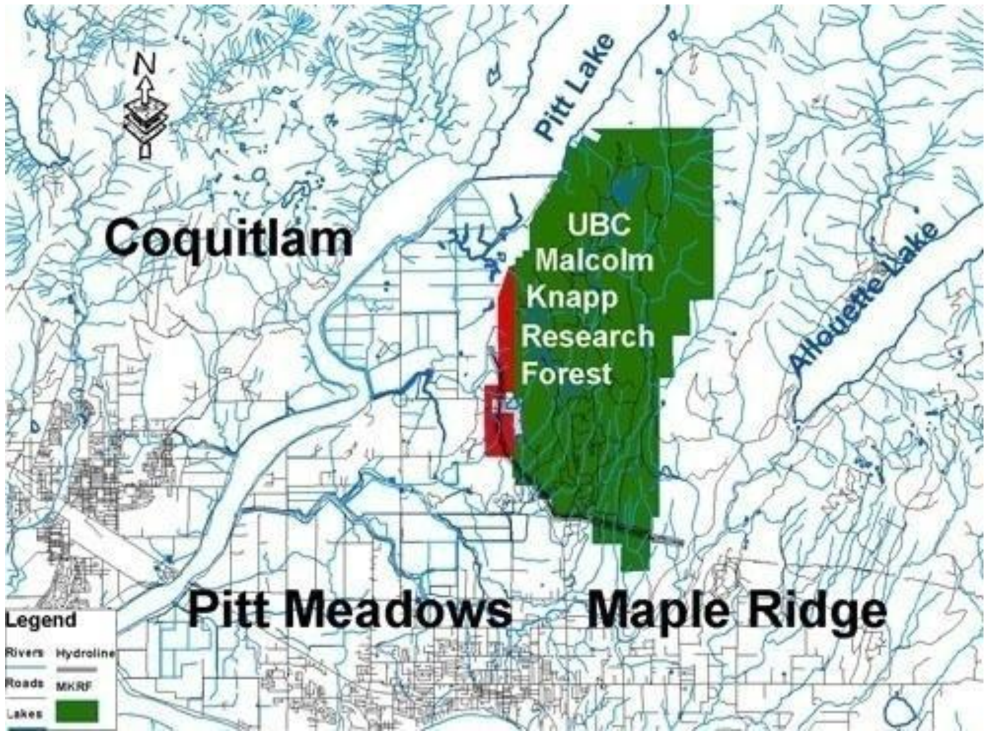


Fig 3.1 Location of the Malcolm Knapp Research Forest. Source:
http://www.mkrf.forestry.ubc.ca/general/ecology.htm

3.2.2 Experimental design

Two sets of measurements were taken in MKRF. The first set was within the buffer experiment where I monitored LWD recruitment and conditions in different buffer widths. To provide context for the results for this young (70 year old) stand, measurements were also made in 130 year old and 500+year old stands.

The 10m and 30m, buffer treatments, and unharvested control (70 year old) were replicated 3 times within the riparian buffers experiment. The riparian buffers experiment was implemented in 1998, with harvesting in 1999. LWD transects were established in 2005 and re-measured in 2006 and 2007; 2007 results are reported in this thesis. Stand data for the riparian forest comes from vegetation plots that were established in 1998, with tree status re-assessed in most summers since. These vegetation plots are 15m long and 4m wide and are repeated at 2m and 15m from the stream bank on each side of the stream. These 4 transect clusters are replicated at two locations along the stream within each treatment unit. Additional vegetation plots were added for the mature and old-growth riparian forests in the summer of 2006. The methods and results for the MKRF vegetation plots are reported by Miquelajauregui (2008).

3.2.3 LWD sampling

LWD transects were established up the centre of each stream in the summer of 2005 using the Oregon Protocol (Moore *et al*. 2002) as a basis for sampling and measurements. The LWD transect in each treatment unit is 150m in length. I marked the point of commencement (POC) with a blue ribbon and walked 150 m upstream marking point of termination (POT). Each stream was then divided into reaches whenever there was a major change in orientation of either the stream, or the channel or valley form, or vegetation type. For each reach, the active channel width (ACW) and valley floor width (VFW) were measured 2m from the start of the reach and 2m from the end of the next reach. The bearing, gradient and slope angle of the reach were recorded. The ACW and VFW were used to calculate valley floor index (VFI), this value gives the channel and valley form for the reach. The spanning logs in each transect were tagged with uniquely numbered plastic tree tags, usually near the mid creek on the downstream side. To provide context for the buffers experiment in 2006, I established transects in mature (130 year old) and old growth (500 years +) stands, with 2 stream replicates in each of these older stands.

Table 3.1 Plot matrix of Malcolm Knapp Research Forest.

Experiment	Treatment/Stand age	Age	Block name and No	No of Replications
Buffers	10m buffer	70yrs	C, F, G	3
	30m buffer	70yrs	D, H, Sk	3
	Unharvested control	70yrs	SC, MK, EC	3
Stand age	Unharvested control	70yrs	SC, MK, EC	3
	Mature	130yrs	Red trail,1868k	2
	Old Growth	500yrs	Knapp north, Knapp south	2

The criteria for the downed trees that were tagged and measured include: fallen or windthrown since 1998, at least a portion of the log length within the active channel width, greater than 7.5cm in diameter at the mid creek, and in decay class 1-4. I used the five class decay classification (Table 2.2) because it is extensively used in the U.S Pacific Northwest (Appendix 3), and it deals with wood soundness or structural integrity as an explicit part of the classification. In this classification system, recently felled trees (approximately 1 year) constitute the first decay class. Miquelajauregui (2007) documented windthrow and standing tree mortality in the MKRF riparian buffers experiment. She found that windthrow in cutblock edges and buffers was greatest in the first 1-2 winters following harvest of adjacent timber, however some windthrow occurred in subsequent years. To decide whether the logs fell down before, immediately following, or several years after the harvest in 70yrs, 130yrs and Old growth, I estimated the age of regeneration and revegetation of the exposed pit and rootwad. The presence of vegetation and litter on the log was also taken into consideration.

Tagged trees were classified according to: status (dead leaning, dead uprooted, dead broken, and live uprooted); species; and decay class. The distance of the tree from the transect POC was recorded. The bearing to the top, DBH, length within the active channel width, and total length of each tree were also recorded (See Appendix 1 for description of variables). If the tree was broken into pieces within the active channel width, those pieces (logs) were recorded as a, b and so on. For each log, the base diameter, mid-creek diameter, top diameter, log length, height above creek, log angle, span length and length mid creek were recorded. Logs were classified according to log end conditions (e.g. rootwad attached to bole, cut ends, broken ends). Where logs were elevated above the bankfull height of the stream channel (e.g. height above stream > 0 cm), they referred to as ‘spanning’ logs.

3.2.4 Analytical approach

The experimental design is a completely randomized design with one factor Treatment (with three levels Control, 10m and 30m for buffer experiment and 70yrs old, 130yrs old and old growth for stand age experiment). The sampling unit is a reach. I used general linear model (GLM, SAS Institute Inc., Cary, NC) to determine if diameter at mid creek, number of logs in decay class (1, 2, 3, and 4), in-creek and spanning logs varied significantly among treatments. The corrected error term i.e. block nested with treatment is used as error term (Table 3.2). The general model with source, degrees of freedom, the mean square formula and corrected error term used for testing the significance of the particular factor is given in Table 3.2.

Table 3.2 General model for ANOVA design for buffer and stand age experiment

Source	df formula	MS	F ratio
t	t-1	MST	MST/MSE
r(t)	t(r-1)	MSE	
Total	r(t)-1		

Where t is treatment (10m, 30m and unharvested control for buffer experiment and 70yrs unharvested control, 130yrs and old growth for stand age experiment) and r is the number of replications

Multiple linear regression was used for predicting LWD height above the stream. Pearson correlation coefficients were used for checking the correlations between variables (Appendix 6 and 5). Variables that were strongly correlated with height above stream were tested for inclusion in the model. Transformation of variables was used where it improved model fit.

3.3 Results

A total of 464 logs (spanning and in-creek) were recorded in the transects (all buffer widths and stand ages). Even after 8 years following harvesting and the post-harvest pulse of windthrow, the majority of logs in the 10m and 30m treatments were still elevated above the creek (Fig 3.2). In the unharvested control almost all downed logs were elevated above the creek. Of all the windthrown trees in Malcolm Knapp (n=464) the dominant orientation was northwest (Fig 3.3) followed by southwest, southeast and northeast. Most logs were oriented approximately perpendicular to the stream channel (Fig 3.4).

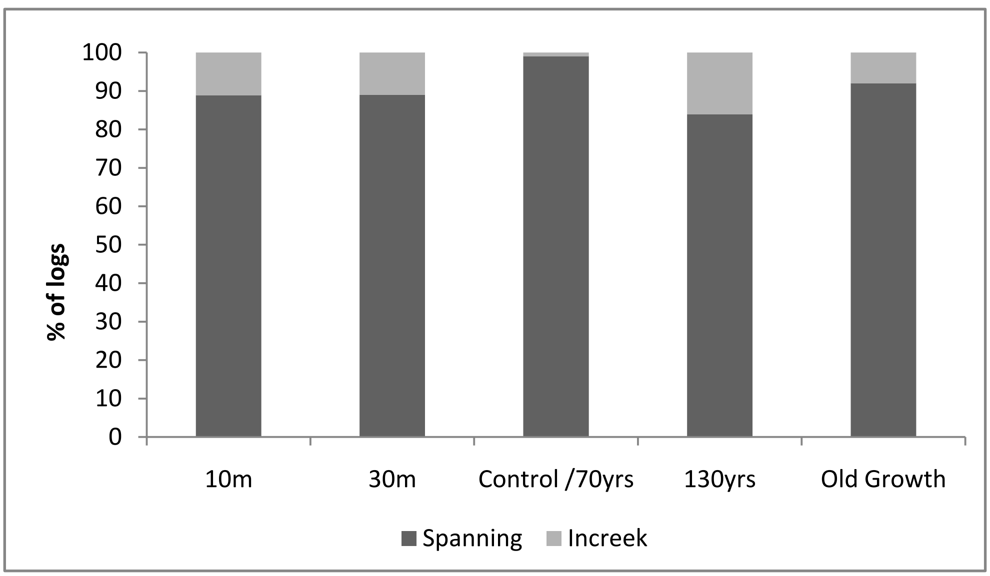


Fig 3.2 Average percent of elevated and in-creek logs by treatments. The 10m, 30m, and Control are in an evenaged stand established following logging and wildfire in the early 1930’s.

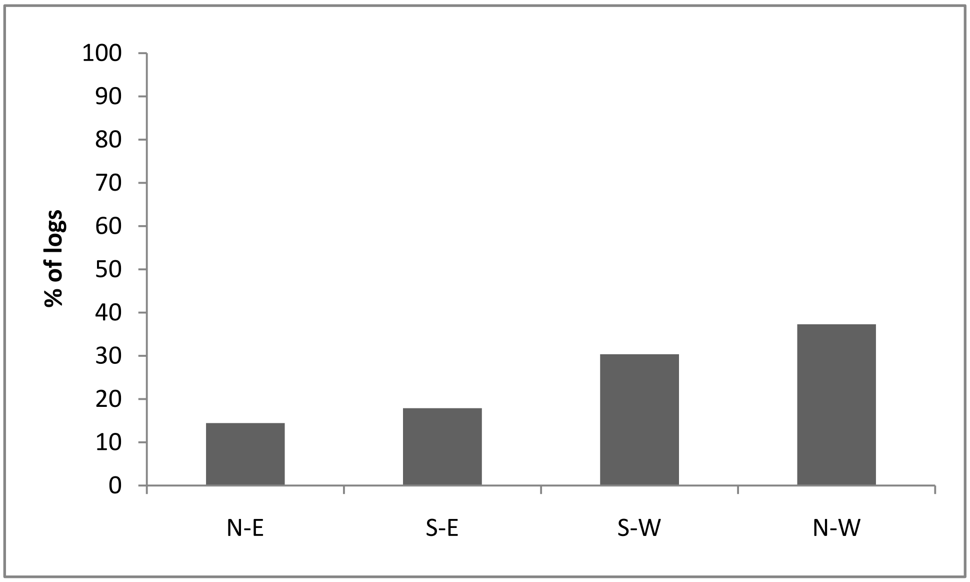


Fig 3.3 Overall percent of logs by directions, all treatments. (n=464)

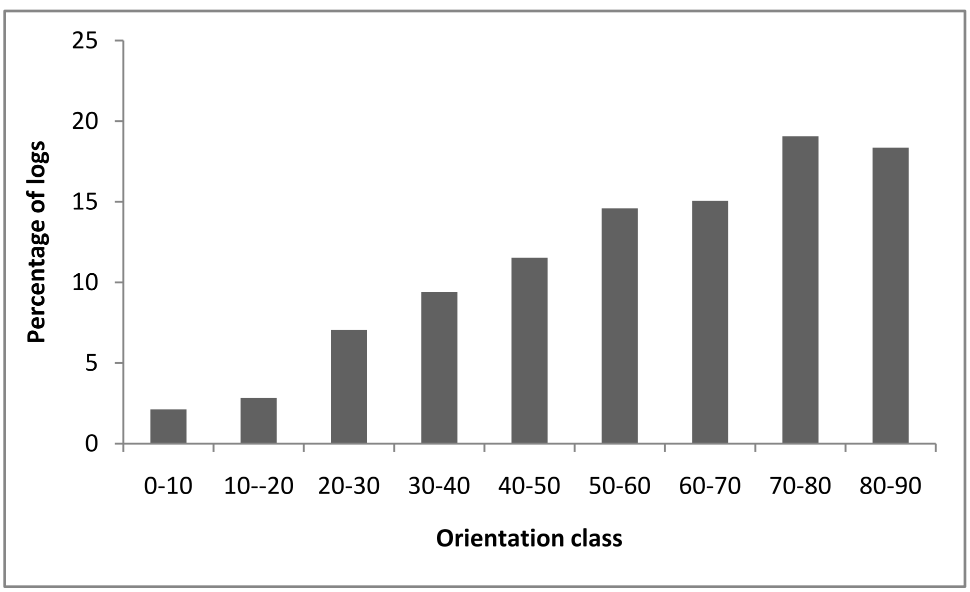


Fig 3.4 Percentage of logs (n=425) by orientation class in degree where 0º is parallel to stream and 90º is perpendicular to stream.

Table 3.3 Analysis of variance results for buffer and stand age experiments. Bold letters means significant results using an α =0.05.

	p-Value	
Variables	Buffer exp	Stand age
No. of logs in decay class 1	0.5408	0.5853
No. of logs in decay class 2	0.2047	0.4423
No. of logs in decay class 3 and 4	**0.0101**	**0.0098**
DMC	0.8755	0.5639
No. of In-creek lwd	0.0605	0.0835
No. of Spanning lwd	0.1734	0.4684

The average number of spanning logs was higher in the unharvested control followed by the 30m and 10m treatments (Fig 3.5). However there was significant variability and therefore no statistically significant difference among the treatments. With increased stand-age, there was a decrease in the average number of spanning logs (Fig 3.5). There were more in-creek logs in the 10m and 30m buffers than in the control. However, there was no clear effect of stand age (Fig 3.6).

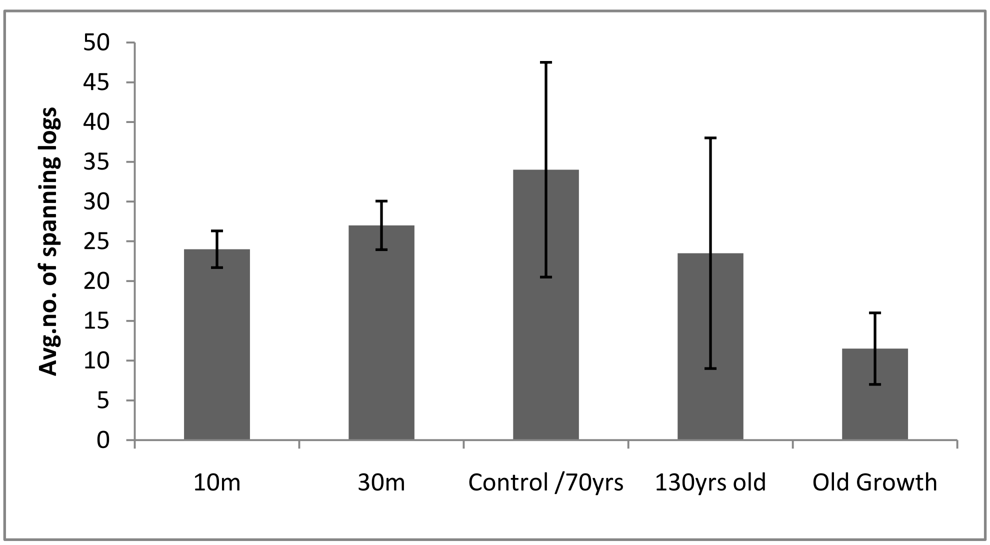


Fig 3.5 Average no. of spanning logs (height above stream >0) >7.5cm diameter at mid creek by treatment, all species, all decay class with SE bars. The 10m, 30m, and Control are in an evenaged stand established following logging and wildfire in the early 1930's.

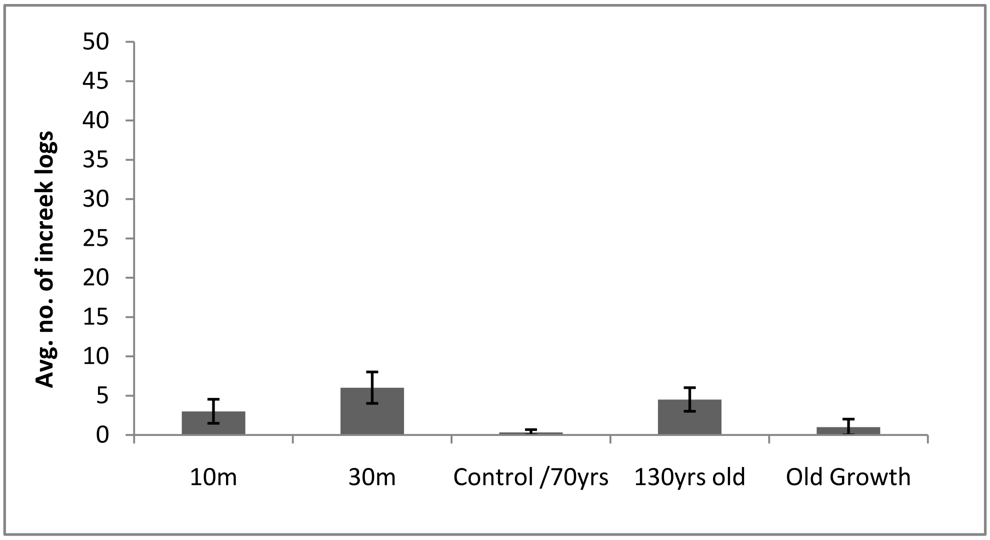


Fig 3.6 Average no. of in-creek logs (height above stream = 0) >7.5cm diameter at mid creek by treatment, all species, all decay class with SE bars. The 10m, 30m, and Control are in an evenaged stand established following logging and wildfire in the early 1930's.

The average number of recently downed trees (decay class 1) was higher in the 70 year old unharvested control (Fig 3.7). Similarly the average number of logs in decay class 2 was higher in the unharvested control (Fig 3.8). There was significant difference in average number of decayed logs in buffer and stand age experiment (Table 3.3). There were more logs in decay classes 3 and 4 in the 30m buffer and the 130 year old stand (Fig 3.9). The proportion of logs in advance stage of decay was higher in in-creek logs than for spanning logs (Fig 3.10). Interestingly there were few logs in advanced stage of decay that were still spanning the creek.

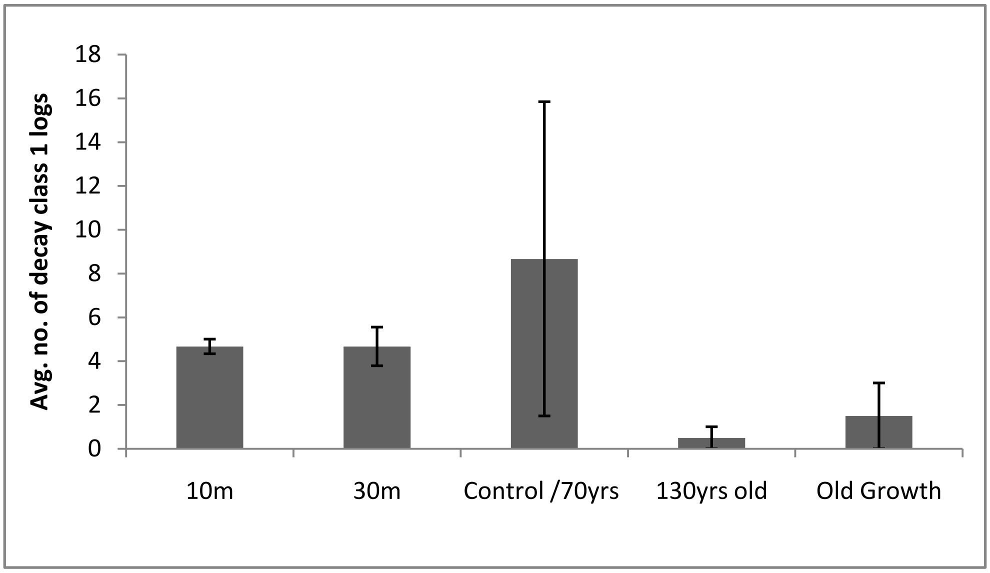


Fig 3.7 Average number of recently downed trees (decay class 1) by treatment with SE bars. The 10m, 30m, and Control are in an evenaged stand established following logging and wildfire in the early 1930's.

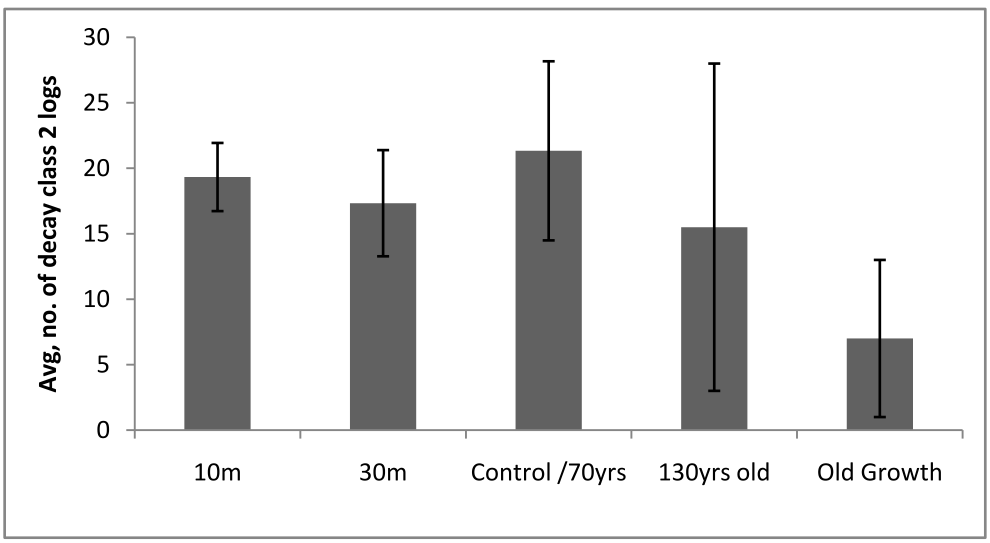


Fig 3.8 Average number of logs all size class in decay class 2 by treatment with SE bars. The 10m, 30m, and Control are in an evenaged stand established following logging and wildfire in the early 1930's.

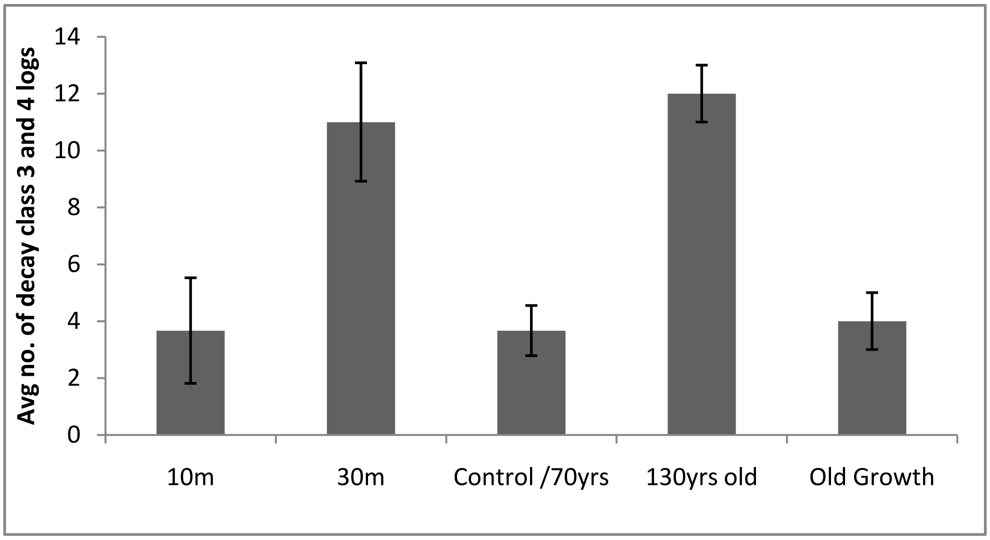


Fig 3.9 Average number of logs all size class in decay class 3 and 4 by treatment. The 10m, 30m, and Control are in an evenaged stand established following logging and wildfire in the early 1930's.

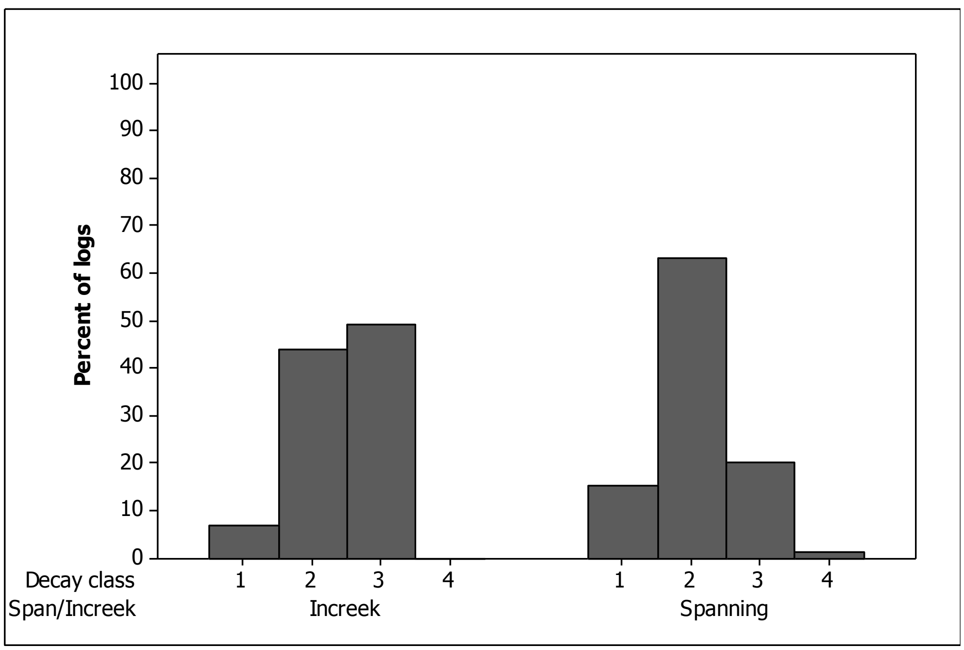


Fig 3.10 Percent of spanning and increek logs by decay classes, all size class.

In the buffer experiment, the mean log diameter at midcreek (dmc) ranged from 14-16cm with the smallest diameters in the unharvested control (Fig 3.11). The mean diameter at mid creek increased with stand age. Debris with the rootwad attached to the bole was more abundant than with cut ends in all treatments (Fig 3.12). Western hemlock was the dominant species, followed by western redcedar (Fig 3.13). A large proportion of conifer logs were in decay classes 1 and 2 whereas logs from deciduous trees were in decay classes 2 and 3 (Fig 3.13). Approximately, 10% of uprooted western redcedar were still alive and spanning the creek whereas all of the uprooted western hemlocks were dead. The major proportions of logs were still suspended over the creek (Fig 3.5 and 3.14) with very few logs (from 10-19cm diameter at mid creek) in the creek. The latter were mostly western hemlock.

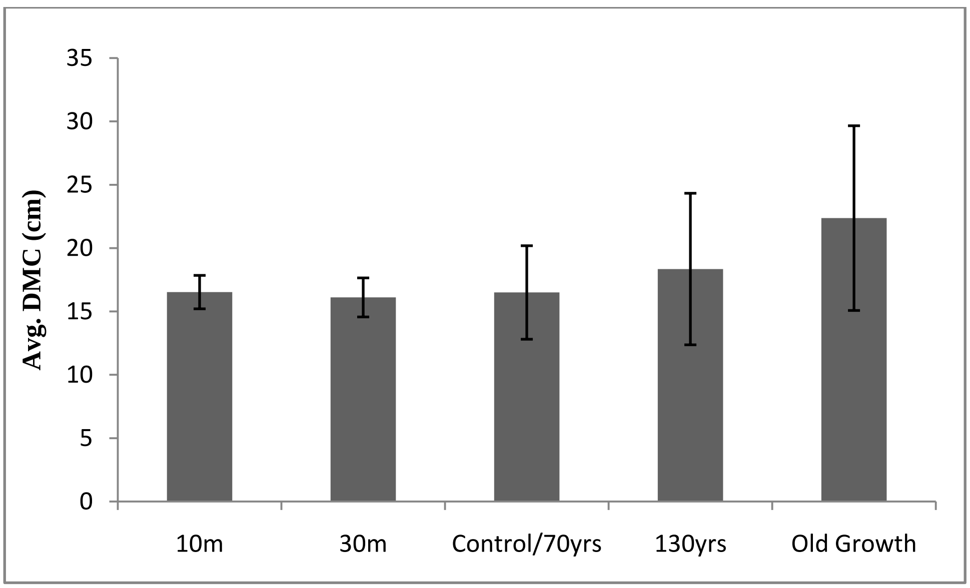


Fig 3.11 Average Diameter at mid creek in cm (dmc) for different treatments with SE bars. The 10m, 30m, and Control are in an evenaged stand established following logging and wildfire in the early 1930’s.

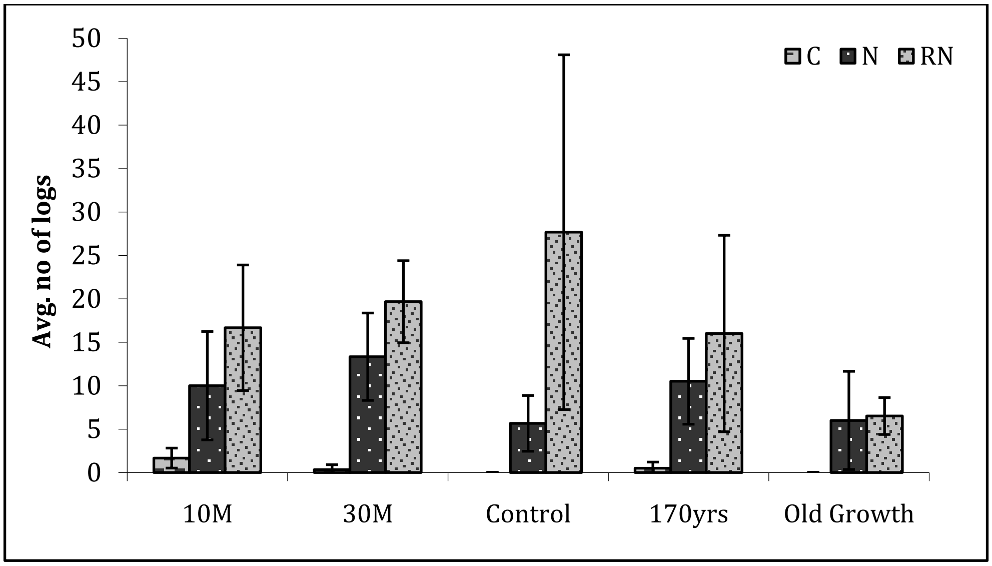


Fig 3.12 Average no. of logs by debris type: C (Cut ends), N (broken ends), and RN (rootwad attached to bole) by treatment with SE bars.

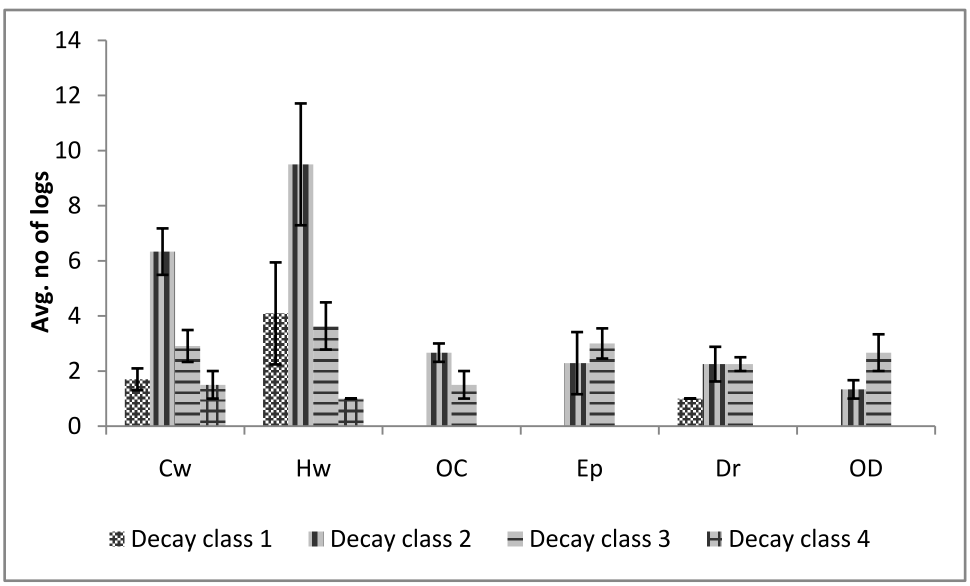


Fig 3.13 Average no. of logs by species among decay classes, where Cw –western redcedar, Hw-western hemlock, OC-other conifers like sitka spruce, douglas-fir, Ep- paper birch, Dr-red alder, OD-other deciduous (big leaf maple, cherry). All treatments with SE bars.

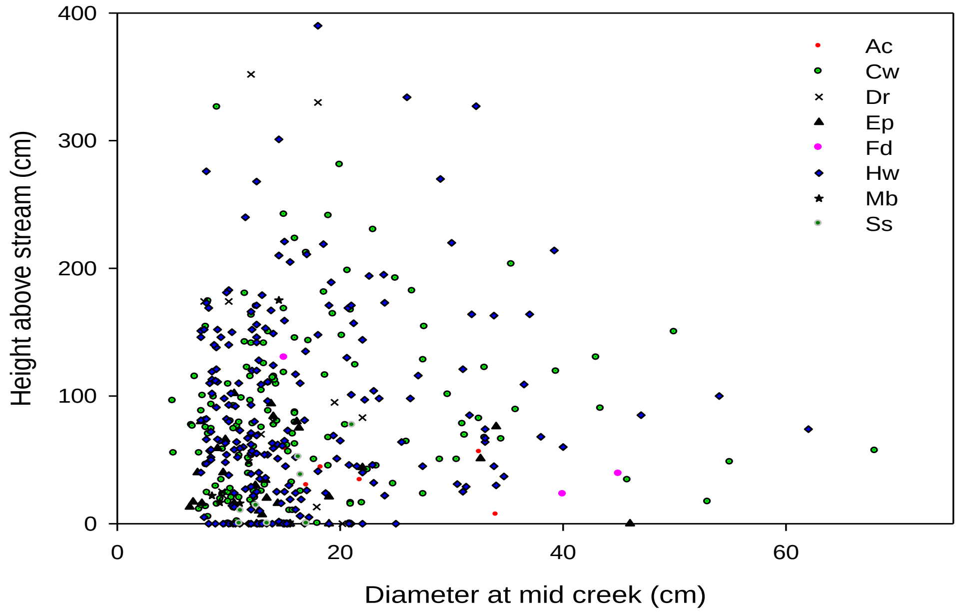


Fig 3.14 Height of logs above bank-full height at mid creek vs log diameter for the species where Ac is black cottonwood, Cw id western red caedar, Dr is red alder, Ep is paper birch, Fd is Douglas-fir, Hw is western hemlock, Mb is big leaf maple and Ss is sitka spruce.

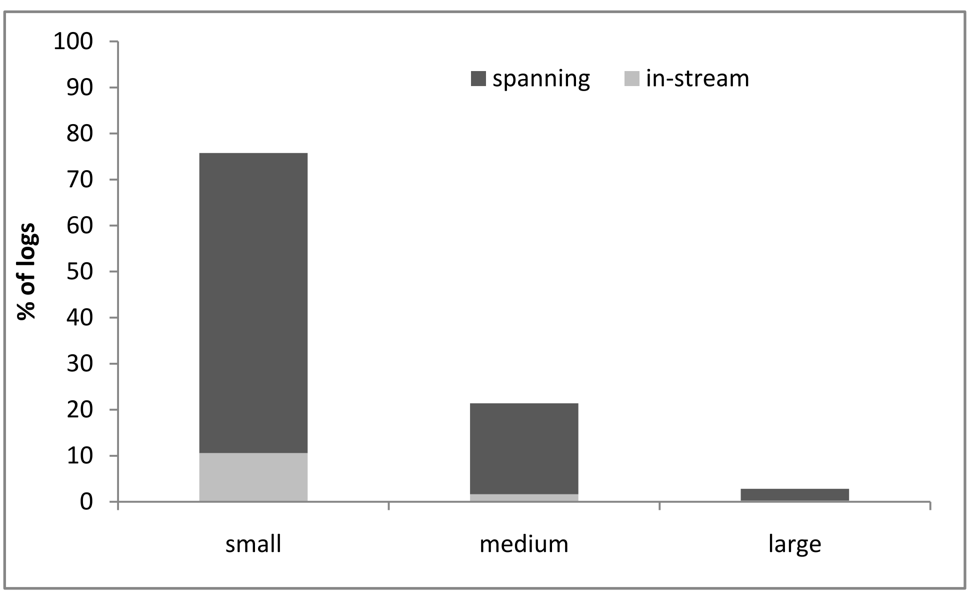


Fig 3.15 Percentage of in-creek and spanning logs (n=425) by DMC classes (where small is 7.5-20cm, medium is 20-40cm and large is >40cm diameter at mid creek.)

Using Pearson's correlation, the variables most strongly correlated with log height above stream (HAS) were decay class (Deccls), reciprocal of valley width index (recivwi) and logarithm of diameter at mid-creek (logdmc) in the buffer experiment (Appendix 6). For the stand age experiment, the best predictors were decay class (deccls) and reciprocal of valley width index (recivwi) (Appendix 7). Decay class was negatively correlated with height above stream for both the stand age and buffer width experiments.

Accordingly, multiple linear regressions were fitted for predicting height above stream by diameter at mid creek, valley width index and decay class for the buffer and stand age experiments. Though the intercept and all the variables DMC, RECIVWI and Deccls were significant (α=0.05), the R^2 value was very low (0.25) Table 3.4. The transformed variables gave a slightly better R^2 value but there were no improvements in heteroscedacity of residual plot and normality. Similarly for the stand age experiment, the intercept and the variables were significant (Table 3.5). The transformed form of VWI was used in the model as VWI was not significant, but the R^2 value remained low.

Table 3.4 Multiple linear regression for predicting height above stream (HAS) cm using diameter at mid creek (DMC) cm, RECIVWI and deccls in buffer experiment.

Variables	Parameter Estimates	Standard Error	p-value	R^2	Root MSE	n
Intercept	112.00	19.95	<.0001			
DMC	1.30	0.50	0.0102			
RECIVWI	115.65	24.24	<.0001			
Deccls	-43.02	6.66	<.0001			
MODEL				0.2463	65.098	259

Predicted HAS= 112 + 1.3 DMC + 115.65 RECIVWI + (-43.02) Deccls

HAS is height above stream, DMC is diameter at mid creek, VWI is valley width index and Deccls is decay class of log. Level of significance α=0.05

Table 3.5 Multiple linear regression for predicting height above stream (HAS) cm using RECIVWI and Deccls in stand age experiment.

Variables	Parameter Estimates	Standard Error	p-value	R^2	Root MSE	n
Intercept	138.08	19.65	<.0001			
RECIVWI	83.37	25.39	0.0012			
Deccls	-36.15	6.69	<.0001			
MODEL				0.23	59.41	185

Predicted HAS= 138.08 + 83.37 RECIVWI + (-36.15) Deccls

HAS is height above stream, RECIVWI is reciprocal of valley width index and Deccls is decay class of log. Level of significance α=0.05

The average length of the logs decreased as decay increased (Fig 3.16). The pattern is same for conifer and deciduous logs. However deciduous logs are shorter than conifers in the same decay class (Fig 3.17).

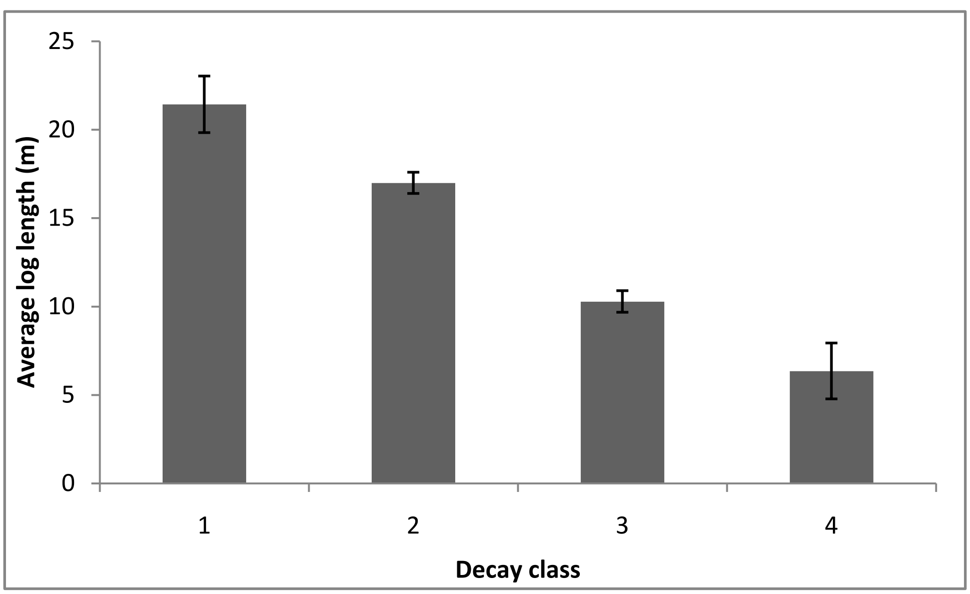


Fig 3.16 Average log length (m) by decay classes for all in-creek and spanning logs, all size classes.

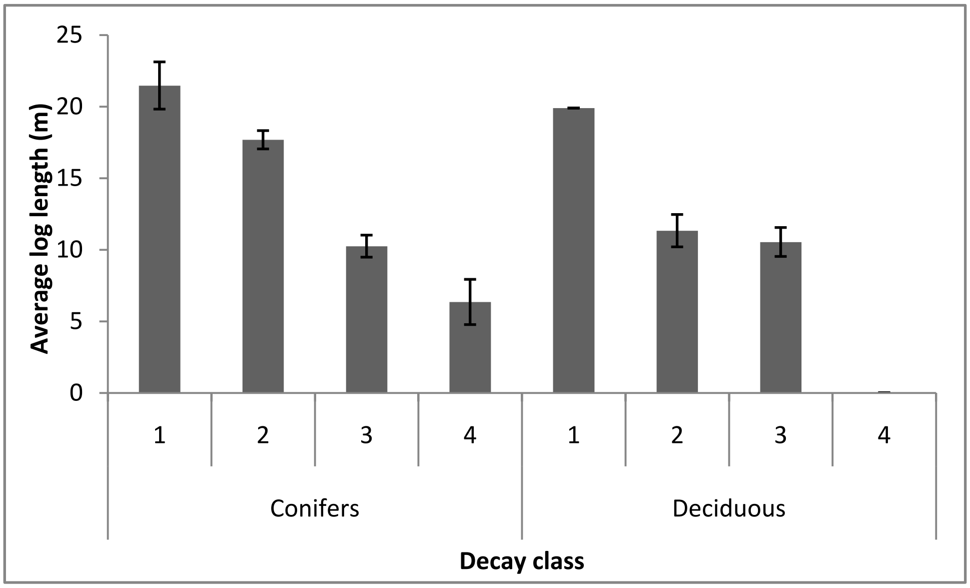


Fig 3.17 Average log length (m) by decay classes and species class (Conifers include western hemlock, western red cedar, sitka spruce, Douglas-fir and Deciduous include Paper birch, red alder, big leaf maple and black cottonwood) for all in-creek and spanning logs, all size classes.

3.4 Discussion

A key reason for retaining buffers adjacent to streams is to supply LWD to the aquatic ecosystem (Van Sickle and Gregory 1990, Grizzel and Wolf 1998). Studies have shown that the windthrow in cutblock edges and buffers is typically greatest in first 1-2 post-harvest winter seasons (Rollerson and McGourlick 2001). Miquelajauregui (2008) found a similar pulse of post-harvest windthrow in the MKRF buffers experiment. I found that even after eight years of harvest approximately 90% of windthrown logs were still spanning the creek in the 10 and 30m buffers. This is consistent with the results of Wei (2005 a) and Chen *et al*. (2006) who also found the majority of LWD was located above the bank-full height in small sized streams in the Interior of BC. As stated by Grizzel and Wolf (1998), suspended debris will do little to influence channel processes in the near future. There are several implications of this finding for debris recruitment modelling. The first is that the connection between the level of post-harvest windthrow in buffers, and the effect of this windthrow on stream channel properties is indirect. Actual recruitment of windthrown material into the stream may take place over decades following the pulse of post-harvest windthrow. Secondly, many windthrown logs enter the creek channel only after they have become decayed.

Windthrow as a source of LWD recruitment is ignored in other models except CWD (Bragg *et al*. 2000), in which users specify rate of windthrow as a fraction of live tree per year. Hairston-Strang and Adam (1998) demonstrated that windthrow increased LWD loading in Oregon through modeling.

In a managed forest landscape, windthrow in riparian buffers is likely the most significant mechanism by which LWD is recruited to small stream channels (Grizzel and Wolf 1998). Grizzel and Wolf (1998) found higher total treefall rates in smaller buffers along smaller streams and 34% increase in within-channel LWD pieces in Washington State. The number of spanning LWD pieces at MKRF is greater than reported in some other studies (e.g. Powell 2006, Jones and Daniels 2008). The studies were conducted in 100 (year) old lodgepole pine and spruce dominated forest in the Foothills Model Forest in west-central Alberta (Powell 2006) and fire disturbed lodgepole pine, black and white spruce in Alberta foothills (Jones and Daniels 2008). This likely reflects differences in study area, stand type (harvest vs. unharvest), and disturbance type.

Riparian buffers are particularly susceptible to windthrow following harvesting (Rollerson and McGourlick 2001, Liquori 2006). Rollerson and McGourlick (2001) found that the percentage of windthrown trees increased as buffer width decreased, and Liquori (2006) found a negative correlation between LWD recruitment and riparian buffer width. Similarly, Martin and

Grotefendt (2001) found high windthow rates in the outer edge of buffers (10-20m from stream) and less windthrow in core of the buffer (0-10m from stream) in Alaska. This difference was not apparent in the 10m and 30m buffers at MKRF.

Buffer width could directly affect the number of stems available for recruitment as LWD. In Southeast Alaska, Martin and Grotefendt (2006) found that 95% of the LWD in streams in buffer units was derived from within 30m of the channel, whereas in the unlogged stand 96% of LWD recruits were derived from within 20m. However, they found that the majority of LWD was coming from within 10m of the channel, 81% and 89% for buffer and unlogged stands respectively. In my study at MKRF, I found the number of spanning and in-creek logs to be similar in the 30m buffer and 10m buffers, and highest in the unharvested control. Stand densities in the 70 year old stands at MKRF are high. Miquelajauregui (2008) found that the unharvested control at MKRF had higher standing tree mortality compared to 10m and 30m buffer treatments over the 8 years following harvesting. This may be due to competition mortality. Postharvest wind damage and increased light from the edges appear to have significantly reduced the competition mortality in the buffers, thereby substantially changing wood recruitment dynamics between buffers and controls.

The orienting effects of wind damage are also important for LWD recruitment modeling. In MKRF, most of the windthrown trees are oriented perpendicular to the stream. Only 2% of logs are parallel to the creek. Wei (2005 a) reported the large majority of LWD in small streams in Interior BC were orientated perpendicular to the stream. This appears to be a general finding with similar results were reported in Rocky mountain streams in northern Colorado (Richmond and Faush 1995), northwest Montana (Hauer *et al*. 1999), in the southern interior BC (Chen *et al*. 2006), the Cascade Mountains of western Washington (Liquori 2006) and Alaska (Robinson and

Beschta 1990). This effect appears to apply to in-creek LWD also, with Richmond and Faush (1995) reporting that smaller streams have greater proportion of perpendicular pool forming pieces than large streams. Bilby and Ward (1989) found LWD to be oriented perpendicular to the flow of stream more often than expected in Washington streams < 7m active channel width but oriented diagonally in stream> 10m width. The picture becomes less clear in larger streams, where stream energy may re-orient LWD (e.g. Chen *et al*. 2006).

There appears to be a general trend that small trees contributed disproportionately to LWD recruitment. In all treatment and age classes in MKRF, 76% of LWD comes from small sized diameter class (7.5-20cm diameter at mid creek), whereas medium sized (20-40cm) and large sized (>40cm) represent 21% and 2.5% respectively. In the 70 year old stand the average diameter of LWD ranges from 15-16cm whereas in 130 years and old growth stands the diameter at mid creek ranges from 20-25cm. Similar results were found in LWD studies in northwest Montana (Hauer *et al*. 1999), where 70% of all LWD was in 10-30cm diameter class. Around 80% LWD in south interior BC were found to be smaller category diameter class (<20cm) in 120 years old stand. Berg *et al*. (1998) also found a similar pattern with logs ranging from 8-25cm diameter class. In subalpine old growth forests, highest percentage of LWD distribution was from smallest size classes (10-30cm) (Richmond and Fausch 1995). The reason behind the preferential recruitment of small LWD is likely the effect of competition mortality. Miquelajauregui (2008) found that windthrown trees at MKRF were larger on average than trees that died standing, but that they were still smaller than the largest trees in the stand.

I was unable to find any research that reported the time for suspended logs to fall into the creek. Grizzel and Wolff (1998) stated that the time between initial recruitment and the secondary phase when logs break apart and enter the channel depends upon species, size and condition of the wood piece. I found a strong negative correlation between the height of log above creek with the decay status of the log and that bigger logs tend to decay slower than smaller ones. At the species level, the behaviour of deciduous tree LWD differs from that of conifers, and some of the redcedar were still alive and undecayed, 8 years after windthrow. The conifer logs were mostly in decay class 1 and 2 whereas the deciduous logs were in the 3rd and 4th decay class. This trend toward shorter persistence was also reported by Harmon *et al*. (1986). Average log lengths tended to decrease with increase in decay. Similar results were reported from Jones and Daniels (2008) and Powell (2006). It is not surprising that the average log length is therefore shorter for deciduous LWD. However, within a given decay class, the average log length of deciduous is slightly shorter than conifers. McDade *et al*. (1990) also found the length of LWD pieces to be less in hardwood than in conifers.

The relationship between decay and log breakage is interesting and important for LWD recruitment modeling. One might expect that decaying logs would fail near mid suspension. However, many logs appeared to decay more rapidly from the upper broken end where it was in contact with the soil, breaking into relatively short chunks. Highly decayed logs may be less useful for structuring stream channels when they finally drop into the streams, particularly if they are broken into short pieces. This is an area that should be investigated further.

In addition to Grizzel and Wolff's (1998) predictions, I found that the height above stream was also correlated with the orientation of the log relative to the stream, the diameter of the log at mid creek and the valley width index. Pearson correlation coefficients between the variables showed that the height of log above the bank-full height of the creek will be higher if the log is oriented perpendicular to the stream. If the valley width index (ratio of valley width to active channel width) was high then the height above stream was lower. For estimating the actual recruitment of LWD, it is therefore necessary to characterize species and diameter specific decay rates, initial log point of germination and orientation, and valley profile.

There are many existing LWD recruitment models like AQUAWOOD (Wei 2005 b), RAIS (Welty *et al*. 2002), STREAMWOOD (Meleason 2001) and CWD (Bragg *et al*. 2000). All these wood recruitment models ignored the position of LWD in the stream. I found that LWD was still in suspended years after it was windthrown in this study. There are many logs in stream in various stages of decay and yet spanning the creek. Being in the suspended condition, LWD pieces cannot contribute a lot to the aquatic ecosystem. They become functional once they are in the creek when they begin to perform the key functions like pool creation, sediment storage, and shaping the channel. So, I personally felt that there should be another component in the model that addressed the time for spanning logs to come in the creek. This enables me to make a conceptual model framework for the spanning logs.

3.5 Conclusion

It is clear from the field data that a majority of the windthrow trees continue to span the creek even eight years after a windthrow event. However, there is no difference in number of logs in different buffer widths. The actual recruitment of logs in a creek is a long term processes which is dependent on a number of factors. There is a need for an extra component in the existing LWD recruitment model that takes spanning logs in consideration and predicts recruitment following a windthrow pulse based on these factors. The proportion of trees falling perpendicular to the stream flow is higher. So these models also need to account for the orienting effects of windthrow.. The frequency of logs with rootwad attached is higher than the broken ends, indicating that windthrow results in more uprooting of trees than breakage. The abundance of

LWD was higher in immature stands than mature and older stands. Not surprisingly the diameter of LWD is more in old growth and mature stands than immature stand; however, in all stands the major portion of LWD came from small diameter class which will end up more quickly in the stream than the big diameter logs. Many windthrown logs are in advanced decay before they enter the stream channel and the implication of this for LWD function in steams needs to be investigated.

4. Postharvest windthrow and recruitment of LWD in riparian buffers on Vancouver Island.

4.1 Introduction

Studies over past decade have confirmed that the removal of LWD from the streams has resulted in loss of fish biomass due to simplification of habitat whereas the addition of LWD has resulted in structuring fish habitat by creating plunge pools and a corresponding increase in fish biomass (Fausch and Northcote 1992). For small streams, windthrow can be the dominant LWD input process from a riparian buffer (Lienkaemper and Swanson 1987). Post-harvest windthrow in riparian buffers and riparian management zones is chronic on northern Vancouver Island (Rollerson and McGourlick, 2001). Most windthrow occurs in the first two winters following harvesting (Scott and Mitchell, 2005). It is not clear how long it takes for windthrown trees to drop into the stream channel where they begin to play a role in stream structure, the factors involved in this process, or the condition these logs are in when they drop into the stream.

The objectives of this study were: 1) Sample a range of riparian buffer and stand conditions in order to document the geometry of post-harvest windthrow in riparian buffers. 2) Investigate the change in condition of stream spanning LWD over time since harvest. 3) Develop the framework for a process model that simulates windthrow supply of LWD to streams within riparian buffers.

The following hypotheses were tested: i) the majority of windthrown trees span the creek, therefore LWD in-creek recruitment does not initiate immediately after a windthrow event; ii) height above creek of spanning LWD is a function of valley form, tree dimensions and log decay class; iii) the height above stream for LWD decreases with time, the rate of decrease is faster for smaller diameter trees, and the rate of decrease varies between species; iv) the abundance of LWD is less in mature stands than in immature stands and the mid creek diameter is larger in mature stands.

4.2 Method

4.2.1 Study site

I sampled streams in two study areas on Vancouver Island, both representative of wind exposed west coast forests with immature and older stands and numerous small streams. Bamfield is on the south west coast of Vancouver Island, 89 km southwest of Port Alberni. Port McNeill is located on the Northeast coast of Vancouver Island. The majority of the sampling units in Vancouver Island were in the CWHvm1 (Coastal western hemlock submontane very wet maritime variant). Mean total annual precipitation varies longitudinally across the Island; ranging from a high of 4387 mm per year on the west coast to 1555 mm per year in the eastern portions, averaging 2682mm (Green and Klinka 1994). Temperatures are moderated by oceanic air masses with a mean temperature in the coldest month of 0.5°C, and mean temperature in the warmest month of 16.3°C. Significant winter snowfall occurs at higher elevations within this subzone, rain on snow events are common. Most of the sampling was in site series 05 and 07 (fresh to very moist, rich to very rich). Soils are typically podzolic, and vary in texture from alluvial sorted sands and silts to loamy glacial tills with high coarse fragment content.

The dominant forest tree species in Vancouver Island are western hemlock, amabilis fir, western redcedar, Douglas-fir, Sitka spruce.Deciduous tree species like big-leaf maple and paper birch are found in open spaces. In both study areas, I focused on stands dominated by western hemlock (Hw) and amabilis fir (Ba), since these are typically more windthrow-prone than mature redcedar dominated stands and are the major stand types on valley side and lower slopes in the vicinity of small streams. I sampled immature stands and mature stands. The immature stands were approximately 100 years old and were of stand-replacing windthrow origin.

4.2.2 Experimental design

In each of those stand types I took a retrospective approach and sampled buffer strips that had been exposed following harvesting of adjacent timber on both sides, for 0-5 years, 6-10 years, 11-15 years and 16-20 years. Our goal was to sample 3 streams at each location in each stand age class and time since harvest class. However, since the buffer requirement for small streams was only brought in 12 years prior to our sampling date, it was difficult to find 11-15 and 16-20 year old buffers. In addition, since the goal was to characterize the fate of windthrown trees rather than evaluate levels of windthrow loss, sampling was restricted to buffers with moderate levels of wind damage. In total I sampled 26 streams (Table 4.1).

The method for stream habitat surveys developed by Moore, Jones and Dambacher (2002) for the Oregon Department of Fish and Wildlife was used as a basis for establishing LWD transects, sampling and measurements. The general sampling and measurement procedure on Vancouver Island was the same as at MKRF (Chapter 3 of this thesis), with the following differences: I surveyed 100m of each stream compared to 150m at MKRF. Streams were divided into reaches using the same procedure as in MKRF i.e. whenever there was a remarkable change in orientation of the stream or change in channel form or valley form or major change in vegetation type. I measured 3 widths within each reach, one at the midpoint and the other two at 1/3rd the distance from the start and end of each reach. Since these were intended to be temporary plots, instead of tagging the LWD, I spray painted the trees with a unique number. Each tree was assigned with two status codes, one for its presumed condition at the time of harvesting of adjacent timber, and a second for its condition at the time of measurement. Secondary log failure type (broken when green or broken when decayed) was also recorded. In addition to the 5 class decay classification, I used the 4 class Weyerhaeuser decay classification with logs recorded as live, decayed firm, decayed soft or decayed very soft. For the logs whose height above the creek was zero, I recorded presence of bank connection, side of bank attached, whether root wad was still attached to the log, and the effect of the LWD on stream channel morphology (e.g. lateral scour, vertical scour under log, vertical scour plunge over log, and debris jam, and sediment storage).

Table 4.1 Location and condition of sample streams.

Location	Stand	Years since harvest (YSH)	Block name & No.	No. of Replications
Bamfield	Immature	0-5yrs	69	1
	Immature	6-10yrs	62, 57	2
	Immature	11-15yrs	53, 59	2
	Immature	16-20yrs		-
	Mature	0-5yrs	60, 61	2
	Mature	6-10yrs	5, 42B	2
	Mature	11-15yrs	63	1
	Mature	16-20yrs	66, 67	2
Port McNeill	Immature	0-5yrs	816 ,818, 238, 238(2nd)	4
	Immature	6-10yrs	594	1
	Immature	11-15yrs	Mogen	1
	Immature	16-20yrs	596	1
	Mature	0-5yrs	803, 4540	2
	Mature	6-10yrs	227, 932	2
	Mature	11-15yrs	207, 240, 208	3
	Mature	16-20yrs		-

Freely spanning trees that were not touching or supporting any other trees were termed ‘clean trees’ and were recorded separately. The suspended length, diameter at suspended end and base, sag, distance to sag point from butt (if any), vertical angle and base side were recorded.

The valley profile was measured by running a transect perpendicular to the riparian buffer at the middle of each reach. This transect ran the full width of the buffer, and I recorded horizontal and vertical distances at regular intervals and at slopebreaks. I also used these perpendicular transects as the centerline of a strip plot to characterize stand conditions. The species, crown class, condition, and DBH were measured for all trees greater than 7.5cm DBH, whose point of germination was located within 2.5m on either side of the transect centerline.

4.2.3. Analytical approach

The experimental design corresponded to a completely randomized design with three factors: location (two levels: Bamfield and Port McNeill), stand maturity (two levels: mature and immature stands) and years since harvest (four levels: 0-5yrs, 6-10yrs, 11-15yrs and 16-20yrs). The sampling unit is a reach. General linear model was used to determine if the no. of logs in various stages of decay and size class, no. of in-creek and spanning logs varied significantly among locations, stand maturity, years since harvest, and their interactions. The variables were calculated at per linear meter of a reach. The error term was corrected using blocks nested with in location, stand maturity and years since harvest as error term (Table 4.2). Differences between means were tested using the least square mean comparison test because of unequal number of replicates. The p-values obtained in each ANOVA were compared with the corrected split alpha. The general model with all sources, the degrees of freedom of each factor or interaction, the mean square formula and the corrected error term for testing the significance of particular factor is given in Table 4.2.

Table 4.2 General model for the ANOVA for Vancouver Island samples.

Source	df formula	MS	F ratio
l	(l-1)	MS(l)	MS(l)/MS(E)
sm	(sm-1)	MS(sm)	MS(sm)/MS(E)
ysh	(ysh-1)	MS(ysh)	MS(ysh)/MS(E)
l*sm	(l-1) (sm-1)	MS(l.sm)	MS(l.sm)/MS(E)
l*ysh	(l-1) (ysh-1)	MS(sm.ysh)	MS(sm.ysh)/MS(E)
sm*ysh	(sm-1) (ysh-1)	MS(sm.ysh)	MS(sm.ysh)/MS(E)
l*sm*ysh	(l-1) (sm-1) (ysh-1)	MS(l.sm.ysh)	MS(l.sm.ysh)/MS(E)
b(l*sm*ysh)	(l) (sm) (ysh) b-1	MS(E)	
Total	b (l*sm) (l*ysh) (sm*ysh)		

Note: l, location; sm, stand maturity; ysh, years since harvest, and b is number of blocks.

Multiple linear regressions were used to establish relationships between the response variable (height above stream) and the predictor variables (decay class, valley width index, DMC). Pearson correlation coefficients were first used to test the correlation between the variables.

4.3 Results

At the stand level, the stems per hectare of standing live trees was greater than standing dead and uprooted trees respectively in both locations (Fig 4.1).Uprooted and broken trees accounted for 8% of all trees within the stand characterization plots. Port McNeill had higher densities of both live and standing dead trees. By species, western hemlock dominated, followed by amabilis fir and western redcedar respectively (Fig 4.2). The Bamfield stands contained some red alder, and big leaf maple while the Port McNeill contained some Sitka spruce. Stems per hectare peaked in the 20 and 30cm DBH classes for both mature and immature stands at both locations (Fig 4.3a and 4.3b). Stems over 1m in diameter were fairly common in the mature stands.

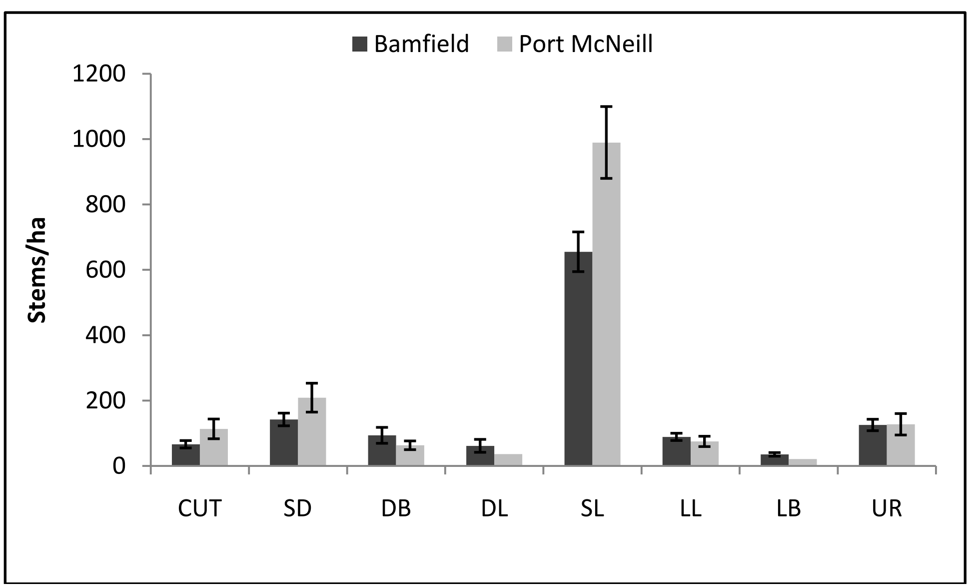


Fig 4.1 Average stems per hectare by tree status (CUT-cut , SD-standing dead, DB-dead broken, DL-dead leaning, SL-standing live, LL-live leaning, LB-live broken, UR-uprooted) and location (Bamfield and Port McNeill) with SE bars.

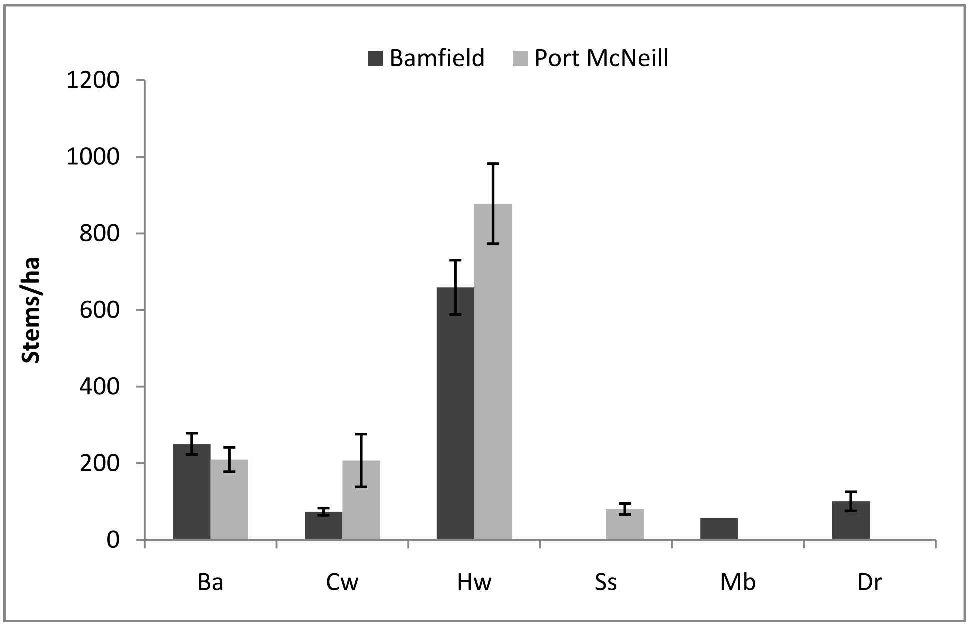


Fig 4.2 Average stems per hectare by live tree species (Ba- amabilis fir, Cw-western redcedar, Hw- western hemlock, Ss-sitka spruce, Mb-maple, Dr-redalder) and location (Bamfield and Port McNeill) with SE bars.

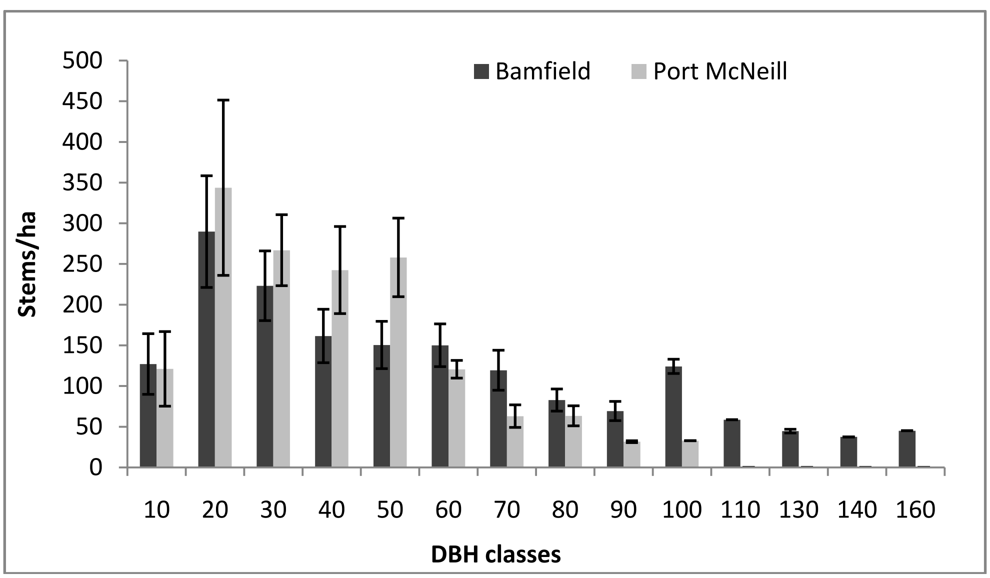


Fig 4.3 a Average stems per hectare by dbh class (10cm dbh classes) and location (Bamfield and Port McNeill) for Immature stand, with SE bars

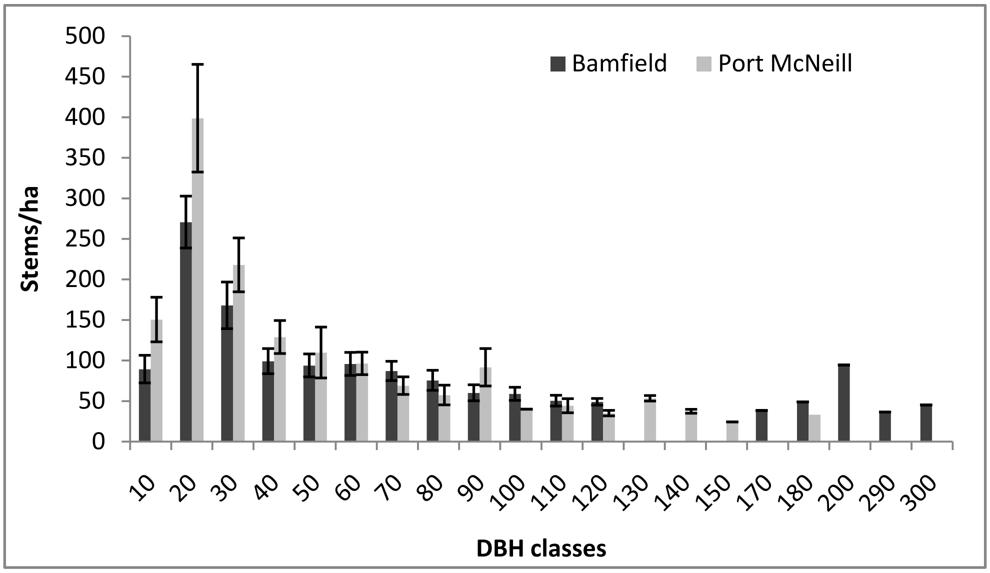


Fig 4.3 b Average stems per hectare dy dbh class (10cm dbh classes) and location (Bamfield and Port McNeill) for Mature stand, with SE bars

By channel form, reaches constrained by alternating terraces and hill slopes (CA) dominated in Bamfield while reaches within constraining terraces (CT) dominated in Port McNeill (Fig 4.4). Both of these categories are considered to have broad channel form (VWI >2.5). The number of reaches with narrow channel form was similar in both locations. By valley form, the number of reaches was higher in constraining terraces (CT) in both locations i.e. broad valley form type (Fig 4.5). There were fewer reaches in the narrow valley form types (SV, MV, and OV).

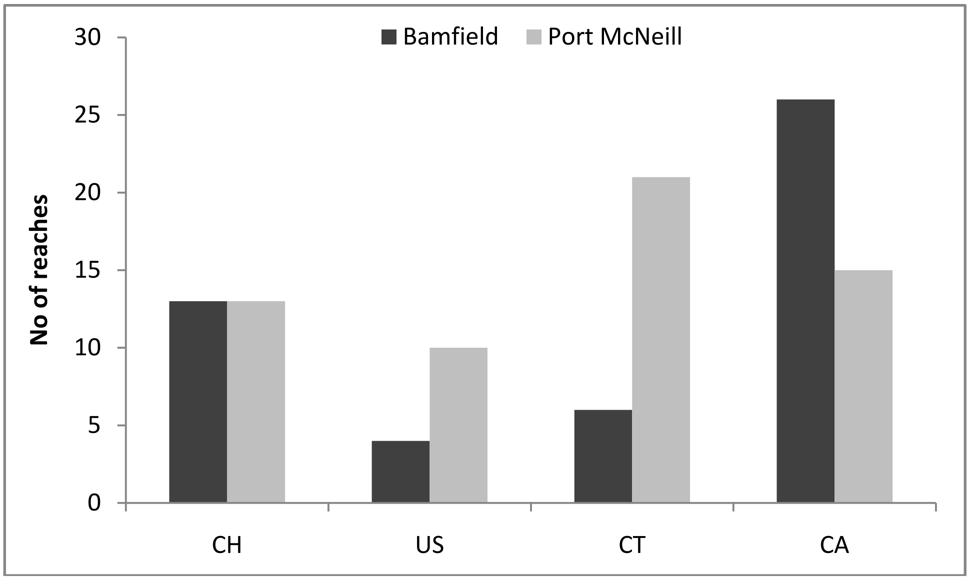


Fig 4.4 No. of reaches by channel form (CH-constrained by hillslope, US- unconstrained predominantly single channel, CT- constraining terraces and CA- constrained by alternating terraces and hill slope and by location (Bamfield and Port McNeill).

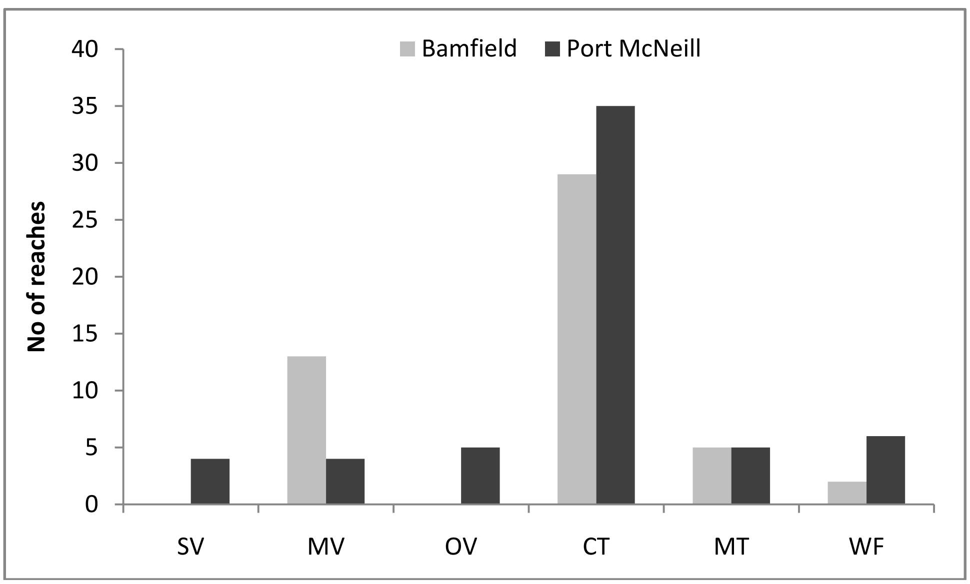


Fig 4.5 No of reaches by valley form (SV-steep V-shaped valley; MV- Moderate V-shaped valley; OV- open V-shaped valley; CT- Constraining terraces; MT- Multiple terraces; WF- Wide active flood plain) and by location (Bamfield and Port McNeill).

Active channel widths (ACW) were a little wider in mature stands than in immature stands in both locations (Fig 4.6). Valley floor widths (VFW) were a little wider in mature stands at Port McNeill (Fig 4.7). Valley width index is the ratio of VFW to ACW and its value reflects whether channel/valley is broad or narrow relative to the stream channel width. This indicates whether the stream is mobile within a flood plain. If VWI is greater than 2.5 then the floor is considered broad. VWI's were somewhat higher in the mature stands at Port McNeill (Fig 4.8).

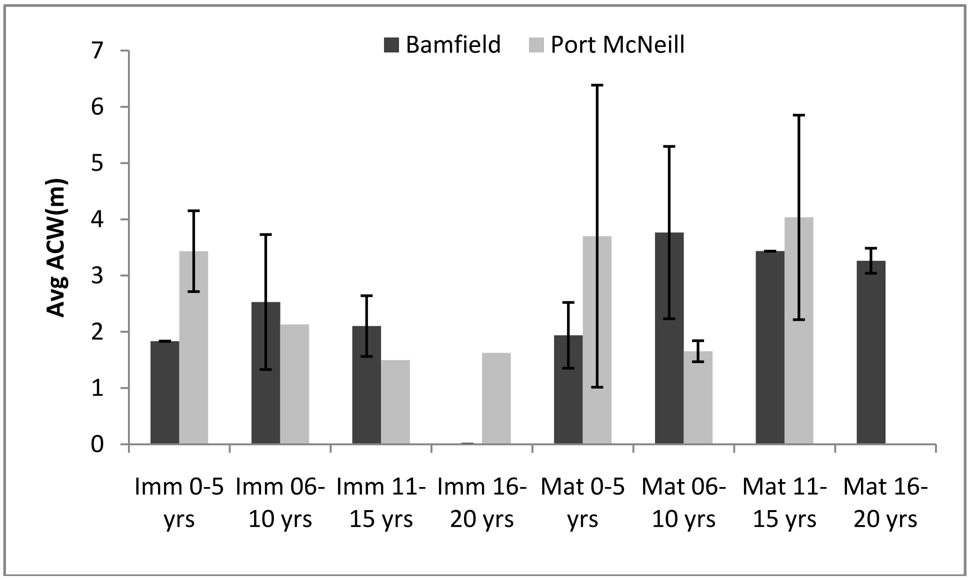


Fig 4.6 Average active channel width (m) (ACW) by stand (Immature and Mature); Buffer age (0-5yrs, 6-10yrs, 1-15yrs and 16-20yrs) and Location (Bamfield and Port McNeill)

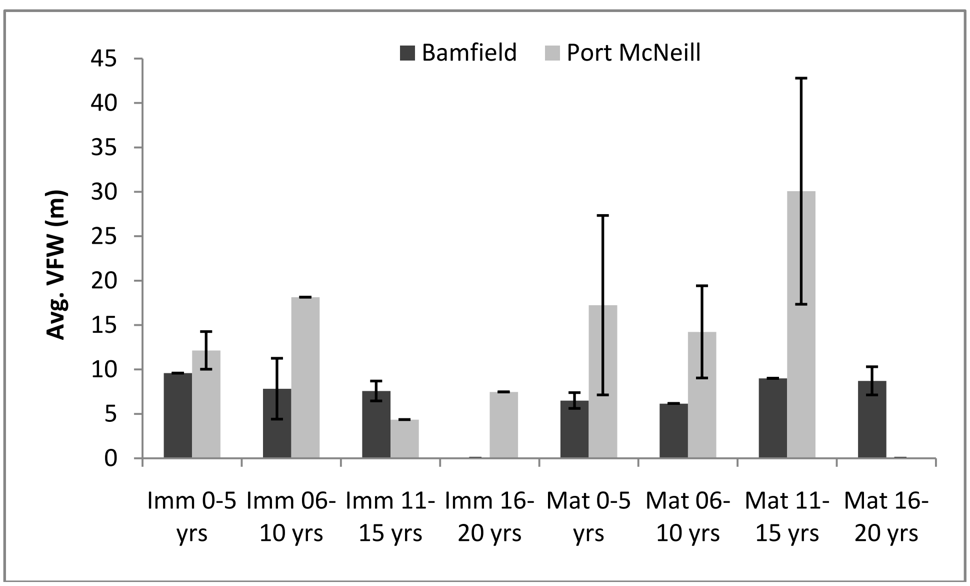


Fig 4.7 Average valley floor width (m) (VFW) by stand (Immature and Mature); Buffer age (0-5yrs, 6-10yrs, 1-15yrs and 16-20yrs) and Location (Bamfield and Port McNeill).

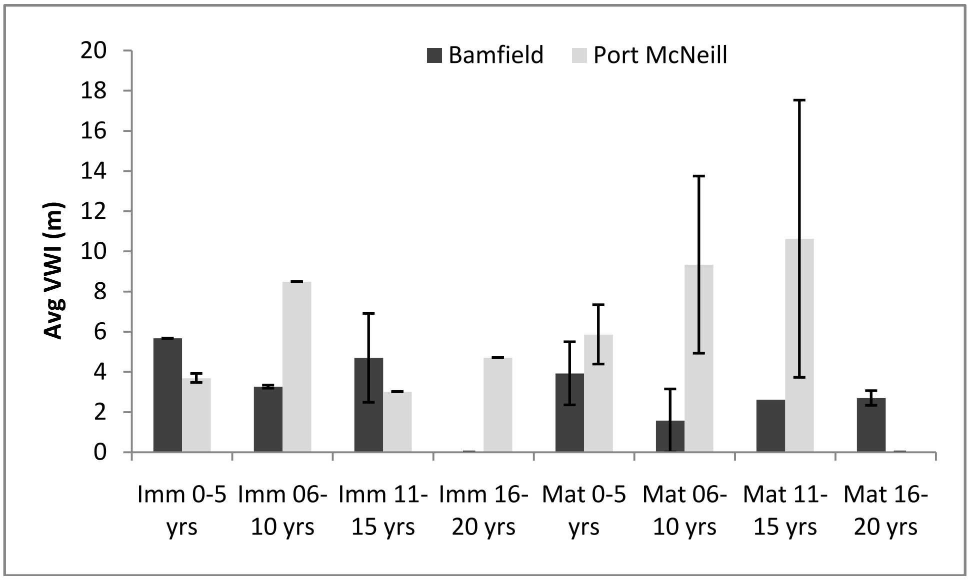


Fig 4.8 Average valley width index (m) (VWI) by stand (Immature and Mature); Buffer age (0-5yrs, 6-10yrs, 1-15yrs and 16-20yrs) and Location (Bamfield and Port McNeill)

The frequency of spanning logs is higher in CT reaches in Bamfield followed by unconstrained channels, whereas in Port McNeill, the frequency is higher in CA followed by hill slopes (CH) and least in unconstrained channels (US) (Fig 4.9). By valley form, the frequency of logs is higher in CT reaches in Bamfield and in MT reaches in Port McNeill (Fig 4.10).

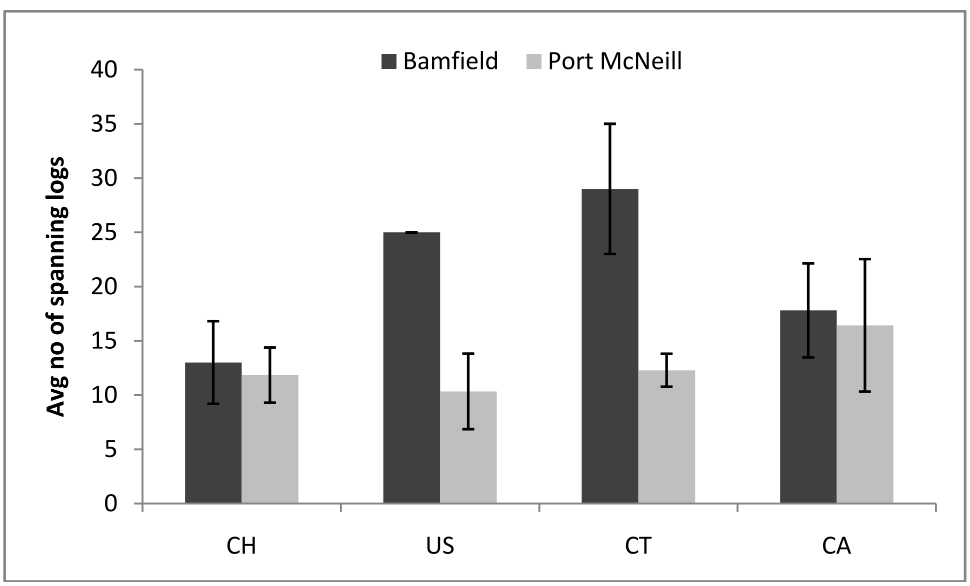


Fig 4.9 Frequency of spanning trees per 100m of stream length by channel form (CH-constrained by hillslope, US- unconstrained predominantly single channel, CT- constraining terraces and CA- constrained by alternating terraces and hill slope) and by location (Bamfield and Port McNeill).

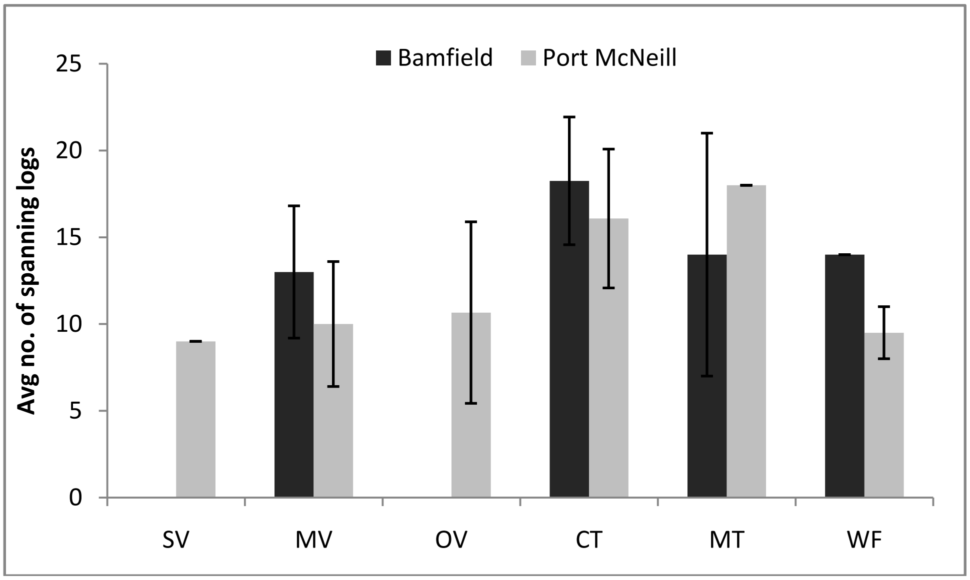


Fig 4.10 Frequency of spanning trees by valley form (SV-steep V-shaped valley; MV- Moderate V-shaped valley; OV- open V-shaped valley; CT- Constraining terraces; MT- Multiple terraces; WF- Wide active flood plain) and by Location (Bamfield and Port McNeill).

Table 4.3 Analysis of variance results for location (L), stand maturity (SM), years since harvest (YSH) effects and interactions. Bold numbers are significant at 0.05 level of significance.

	HAS	DMC	All spanning logs	In-creek logs	Small sized logs (>7.5-20cm dmc)	Medium sized logs (20-40cm dmc)	Large sized logs (>40cm dmc)	Recently downed trees (decay class1)	Decay class 2 trees	Most decayed trees (class 3 and 4)
L	0.7415	0.8937	0.9208	**0.0384**	0.7385	0.5199	0.1469	**0.0041**	0.9867	**<0.0001**
SM	0.7624	**0.0283**	**0.0060**	0.3466	0.0698	**0.0031**	0.7665	**0.0026**	0.1320	0.6404
YSH	**0.0133**	0.8610	0.2412	**0.0019**	0.4111	0.0704	0.6556	**0.0354**	0.6876	**<0.0001**
L*YSH	0.3451	0.8660	0.2617	0.5967	0.7037	0.1225	0.7783	**0.031†**	0.5800	**0.0002†**
L*SM	0.9146	0.8221	**0.0180***	0.7118	0.2051	**0.033***	0.6961	**0.003***	0.1688	0.6655
SM*YSH	0.4464	0.8822	0.0827	0.1496	0.8495	**0.020†**	0.4844	0.4850	0.1111	0.7268
L*SM*YSH	0.7473	0.7293	0.1832	0.7764	0.8802	0.4251	0.7627	0.1965	0.7105	0.7048

*interaction significant at split level α of 0.0125 †interaction significant at split level α of 0.0062

There was a significant difference in the number of spanning logs in mature and immature stands (p= 0.0060) and the number of in-creek logs in YSH (p-value 0.0019) (Table 4.3). After a windthrow event, a large proportion of LWD spanned the creek (Fig 4.11). The number of spanning trees generally decreased (Fig 4.13) and number of in-creek logs generally increased (Fig 4.14) with increased buffer age for both mature and immature stands in Bamfield and Port McNeill. Around 58% of in-creek logs created debris jams in-creek in Bamfield compared to 42% in Port McNeill (Fig 4.12). In Bamfield 42% of windthrown trees (n=347) were oriented towards the northeast followed by northwest (Fig 4.15) and in Port McNeill 47% of windthrown trees (n=145) were oriented towards the northeast, again followed by northwest. So, southerly winds dominate the windthrow processes in both locations.

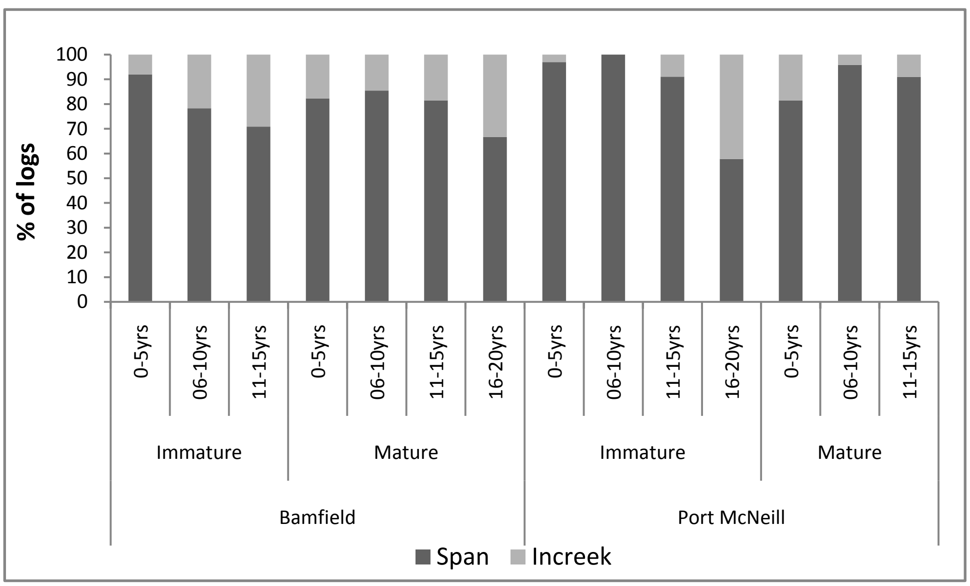


Fig 4.11 Average percent of spanning (height above stream >0) and increek (height above stream =0) logs by location (Bamfield and Port McNeill), stand maturity (mature and immature) and YSH (0-5, 6-10, 11-15, 16-20 yrs).

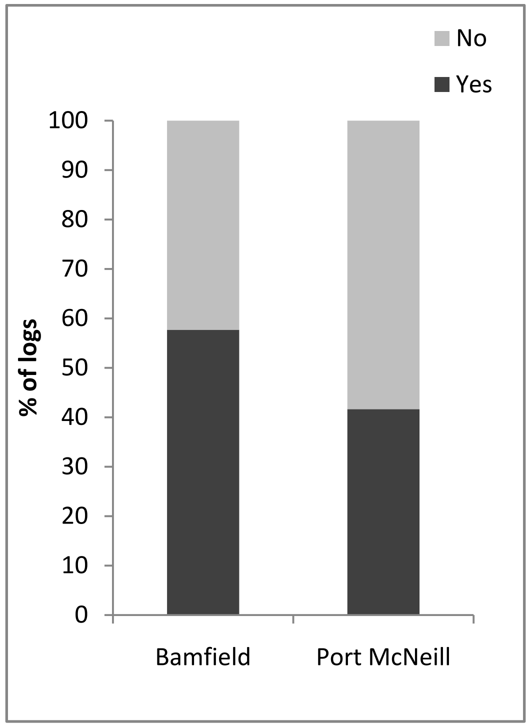


Fig 4.12 Percent of logs in-creek creating debris jam, all stand maturity and years since harvest.

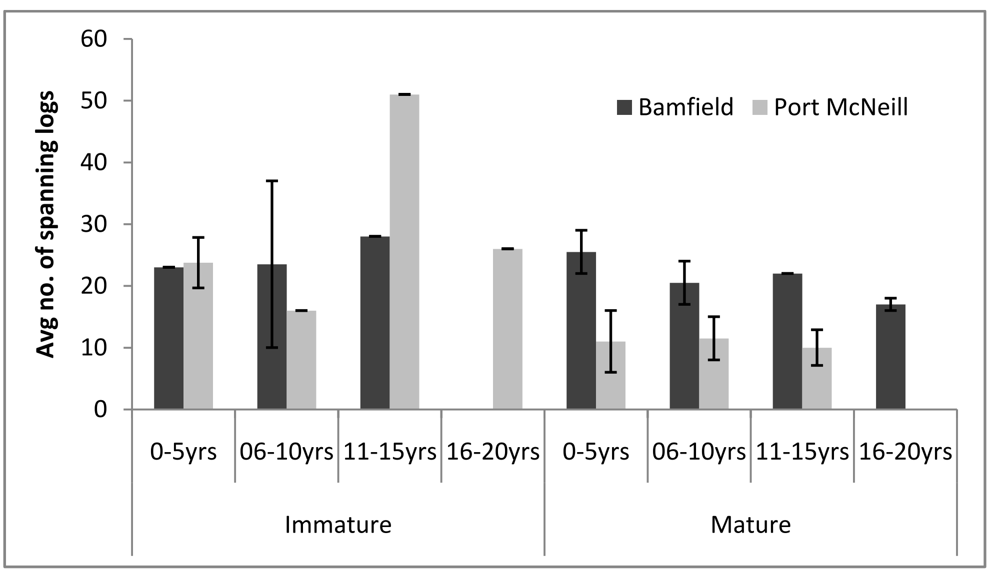


Fig 4.13 Average number of spanning logs (HAS>0) > 7.5cm diameter at mid creek by location (Bamfield and Port McNeill), stand maturity (Immature and mature) and year since harvest (0-5. 6-10, 11-16, 16-20 years) with SE bars.

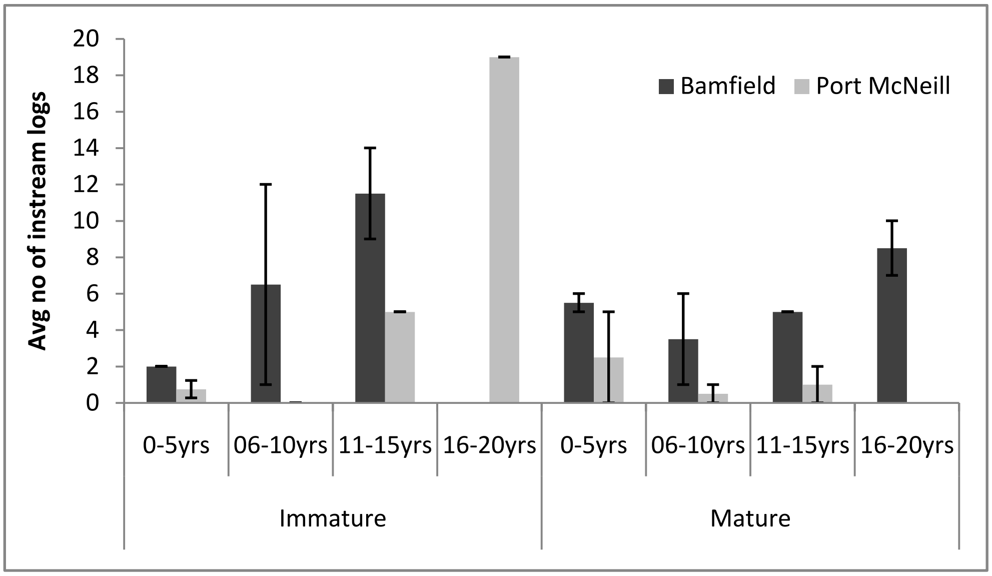


Fig 4.14 Average number of in-creek logs (HAS is 0) > 7.5cm diameter at mid creek by location (Bamfield and Port McNeill), stand maturity (Immature and mature) and year since harvest (0-5. 6-10, 11-16, 16-20 years) with SE bars.

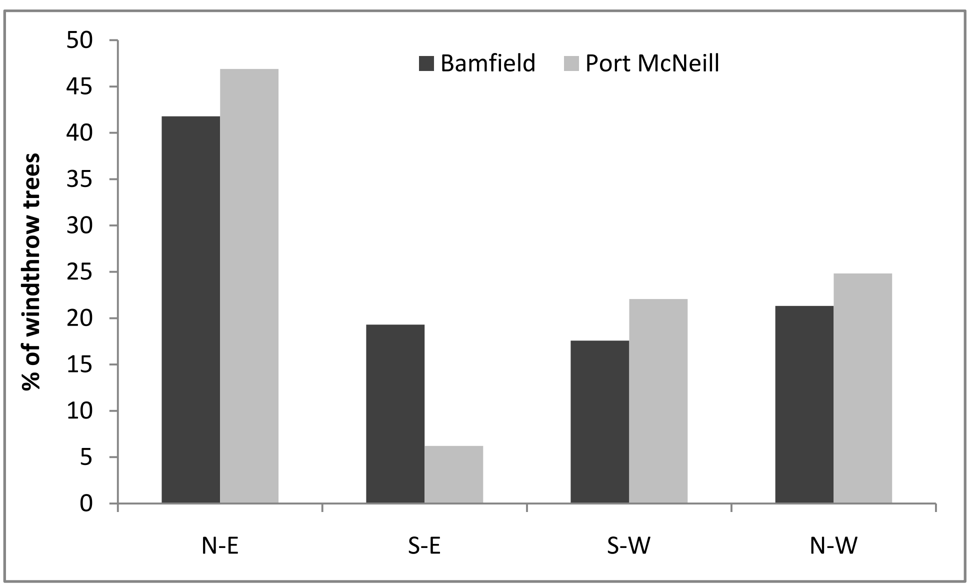


Fig 4.15 Percentage of windthrown trees by Location (Bamfield and Port McNeill) and orientation (toward top of tree).

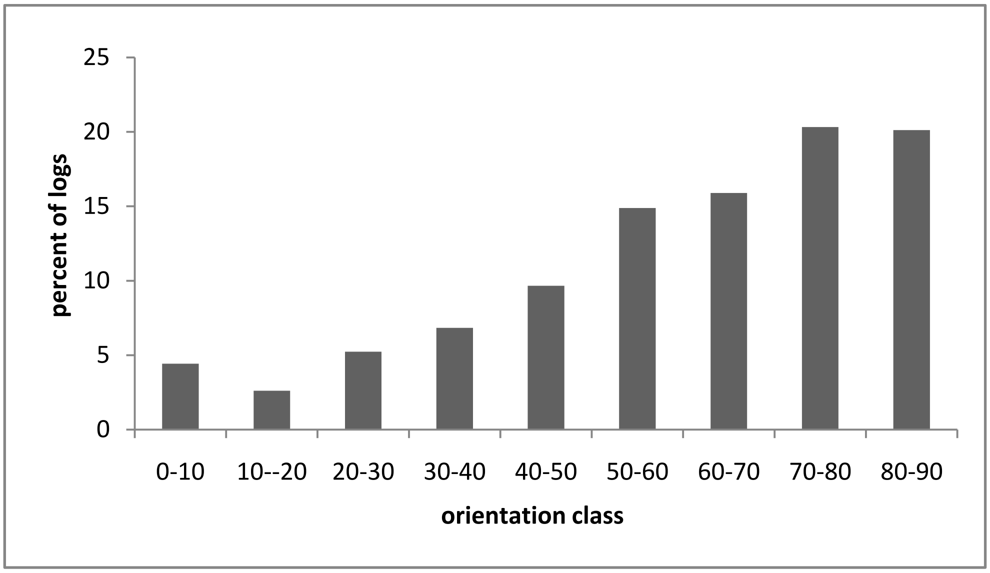


Fig 4.16 Percent of windthrown trees in stream by orientation relative to stream for both locations and all buffer ages; 0 degrees is parallel to stream, 90 degrees is perpendicular to stream.

The large proportion of woody debris is from smaller trees i.e. 15-35cm diameter at mid creek (DMC) in Bamfield and 10-35cm DMC in Port McNeill (Fig 4.17 and Fig 4.18) Larger logs were more likely to be suspended above the creek, although the highest logs above the creek tend to be smaller. There was a significant difference in height above stream in years since harvest (p= 0.013). The average height above stream decreased significantly with increased buffer age (Fig 4.19).

Using Pearson's correlation the best predictor variables for height above stream were years since harvest (YSH), decay class (Deccls), orientation of logs and reciprocal of valley width index (recivwi) and diameter at mid creek (DMC) for Port McNeill (Appendix 8) whereas in Bamfield (Appendix 9) the best predictors were years since harvest (YSH), and decay class (Deccls). In both locations YSH and decay class were negatively correlated whereas reciprocal of valley width index (recivwi) and diameter at mid creek (DMC) were positively correlated.

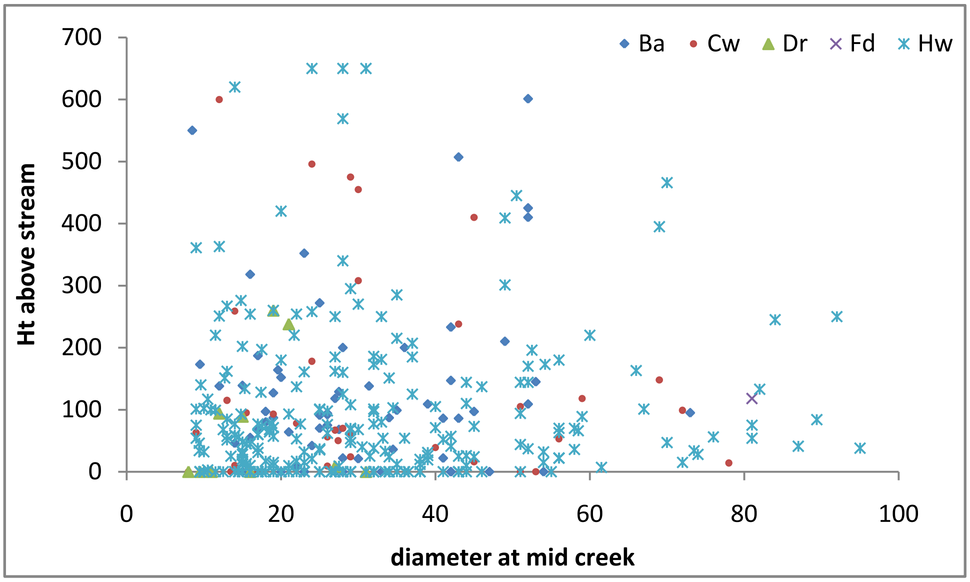


Fig 4.17 Height above stream vs. log diameter at mid creek for all species at Bamfield.

Multiple linear regressions were fitted for predicting height above stream from diameter at mid creek (DMC), decay class (Deccls) and buffer age class (Bufcls) in Bamfield. The intercept and slopes for all 3 variables were significant (α=0.05) but the R^2 value was low (0.27) (Table 4.4). In Port McNeill the regression was fitted using diameter at mid creek, reciprocal of valley width index, decay class and buffer age. The intercept and the slope for the variables were significant (Table 4.5) however the R^2 value was low (0.26). The reciprocal of valley width index was included in the model as the untransformed one was not significant.

Table 4.4 Multiple linear regression for predicting height above stream (HAS) cm using diameter at mid creek (DMC) cm, Decay class (deccls) and Buffer age class (bufcls) in Bamfield. Level of significance α=0.05

Variables	Parameter Estimates	Standard Error	p-value	R^2	Root MSE	n
Intercept	308.62	23.39	<.0001			
DMC	0.64	0.29	0.0303			
Deccls	-81.31	9.30	<.0001			
Bufcls	-16.92	7.49	0.0245			
MODEL				0.2746	125.214	352

Predicted HAS = 308.62 + 0.64 DMC + (-81.31) Deccls + (-16.92) Bufcls

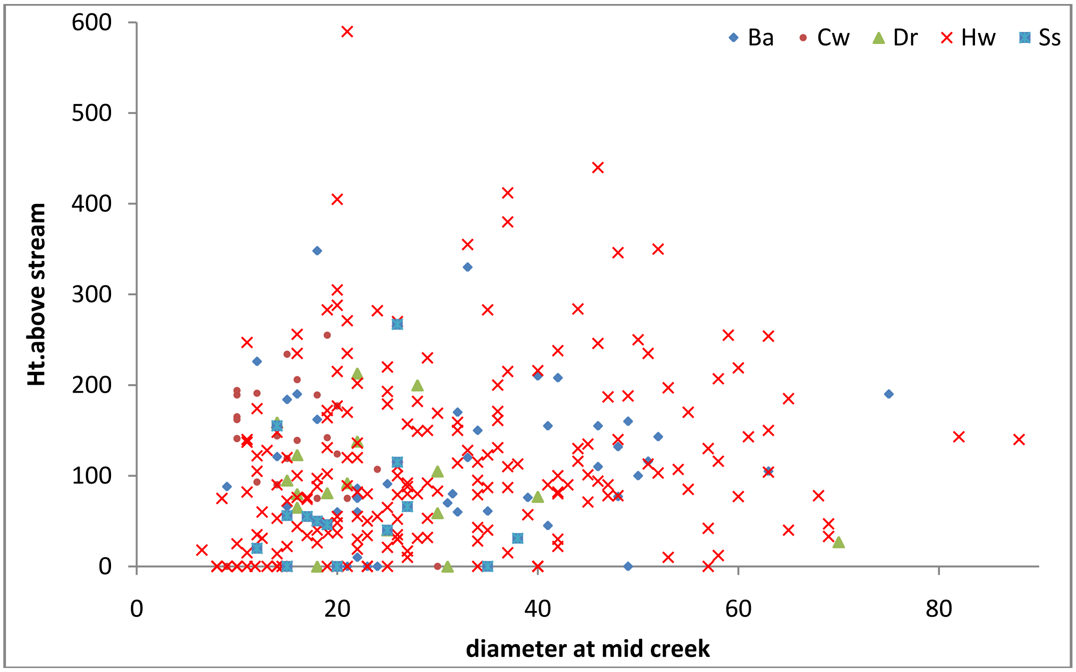


Fig 4.18 Height above stream vs. diameter at mid creek for all species at Port McNeill.

Table 4.5 Multiple linear regression for predicting height above stream (HAS) cm using diameter at mid creek (DMC) cm, recivwi, Decay class (deccls) and Buffer age class (bufcls) in Port McNeill. Level of significance α=0.05

Variables	Parameter Estimates	Standard Error	p-value	R^2	Root MSE	n
Intercept	150.84	20.39	<.0001			
DMC	0.71	0.33	0.0325			
recivwi	72.34	31.15	0.0210			
Deccls	-27.31	6.99	0.0001			
Bufcls	-19.04	5.11	0.0002			
MODEL				0.2610	77.944	254

Predicted HAS = 150.84 + 0.71 DMC + 72.34 recivwi + (-27.31) Deccls + (-19.04) Bufcls

Not surprisingly, DMC was higher in mature stands (Fig 4.20). There was a significant difference in diameter at mid-creek (p= 0.0283) in mature and immature stands. The average number of small sized logs (7.5-20cm DMC class) and medium sized log (20-40cm DMC class) was higher in immature stands in both locations (Fig 4.21 and Fig 4.22). There was no significant difference in the number of small sized logs between location, stand maturity and

YSH whereas there was a difference in number of medium sized logs among mature and immature stands (p= 0.0031). The average number of large sized logs (>40cm diameter class) is in general higher in mature stands (Fig 4.23). Interestingly, the number of logs appeared to increase with buffer age in the immature stands, whereas it was relatively constant with buffer age in mature stands (Fig 4.21 and 4.22).

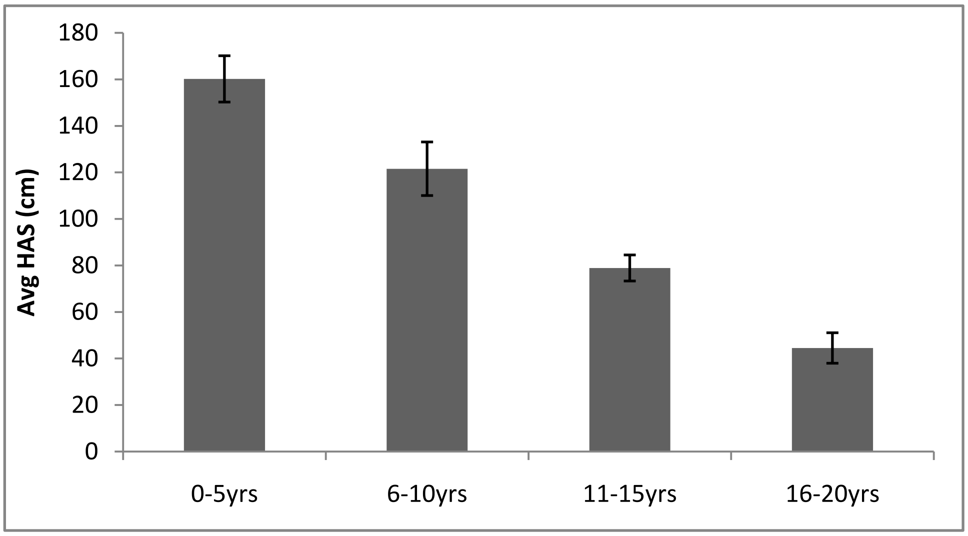


Fig 4.19 Average height above stream (cm) by years since harvest for both locations (Bamfield and Port McNeill).

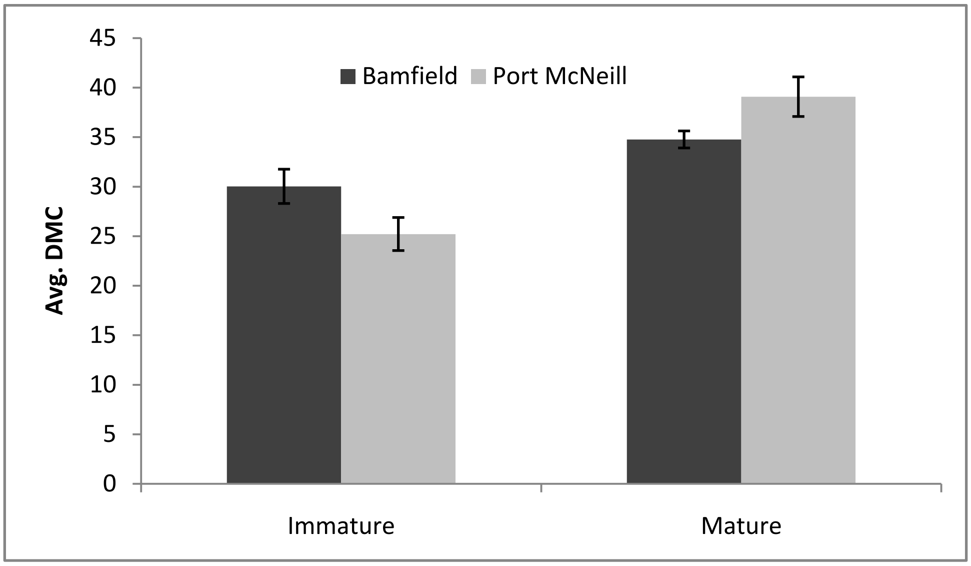


Fig 4.20 Average diameter at mid creek by location (Bamfield and Port McNeill) and stand maturity (Immature and Mature), all size class and decay class with SE bars.

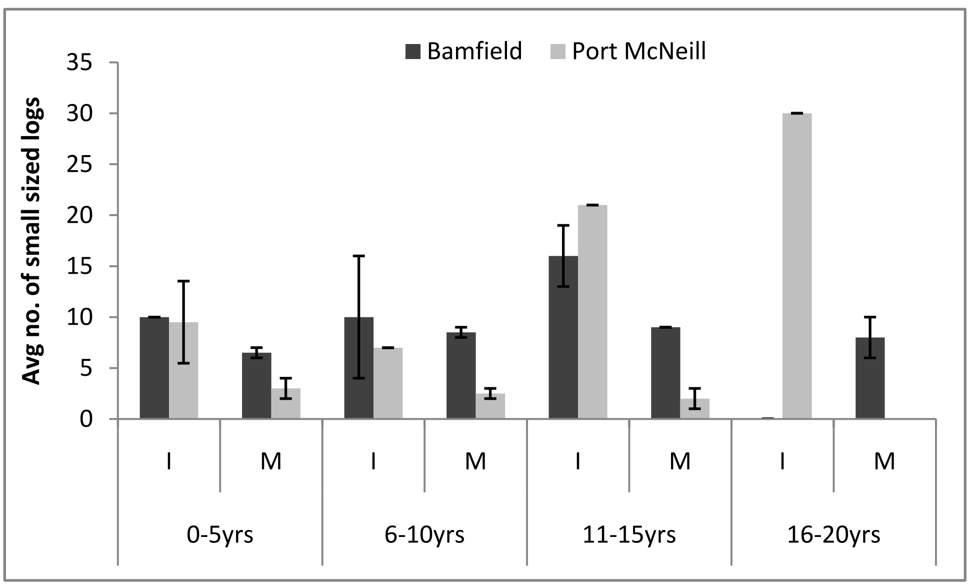


Fig 4.21 Average number of small sized logs (7.5cm-20cm DMC class) by location (Bamfield, and Port McNeill), stand maturity (Mature and Immature) and YSH (0-5, 6-10, 11-15 and 16-20yrs) with SE bars.

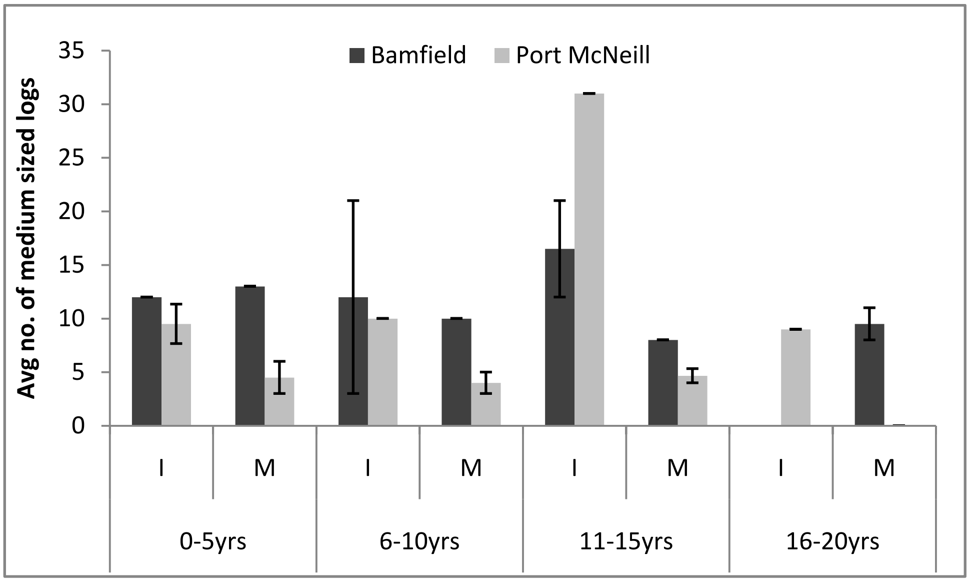


Fig 4.22 Average number of medium sized logs (20cm- 40cm DMC class) by location (Bamfield, and Port McNeill), stand maturity (Mature and Immature) and YSH (0-5, 6-10, 11-15 and 16-20yrs) with SE bars.

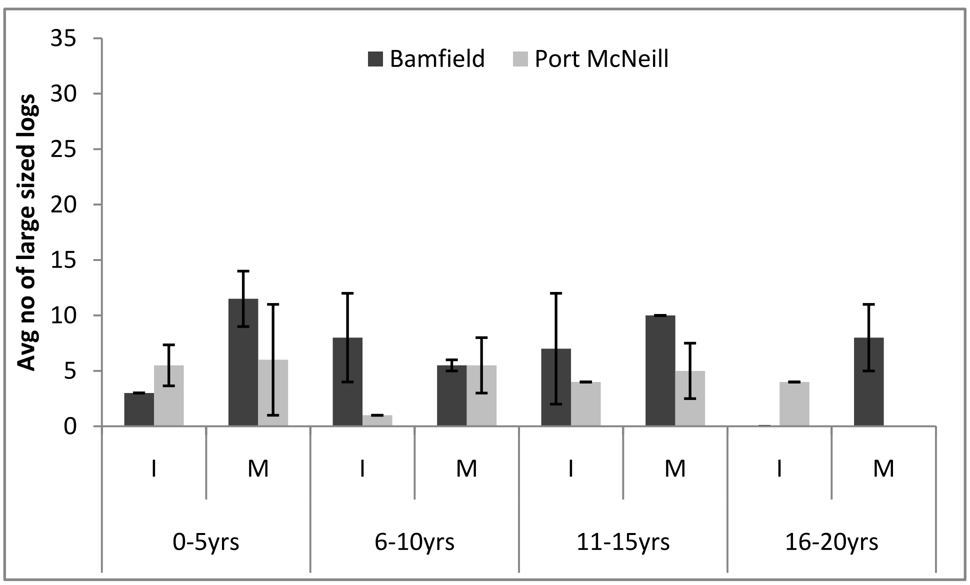


Fig 4.23 Average number of large sized logs (< 40cm DMC class) by location (Bamfield and Port McNeill), stand maturity (Mature and Immature) and YSH (0-5, 6-10, 11-15 and 16-20yrs) with SE bars.

As expected, at Bamfield, the average percent of logs in decay classes 1 and 2 decreased with increased buffer age, while the number of logs in decay class 3 and 4 increased (Fig 4.24). The pattern was less clear at Port McNeill, perhaps due to periodic addition of fresh windthrow in older buffer age classes (Fig 4.25).

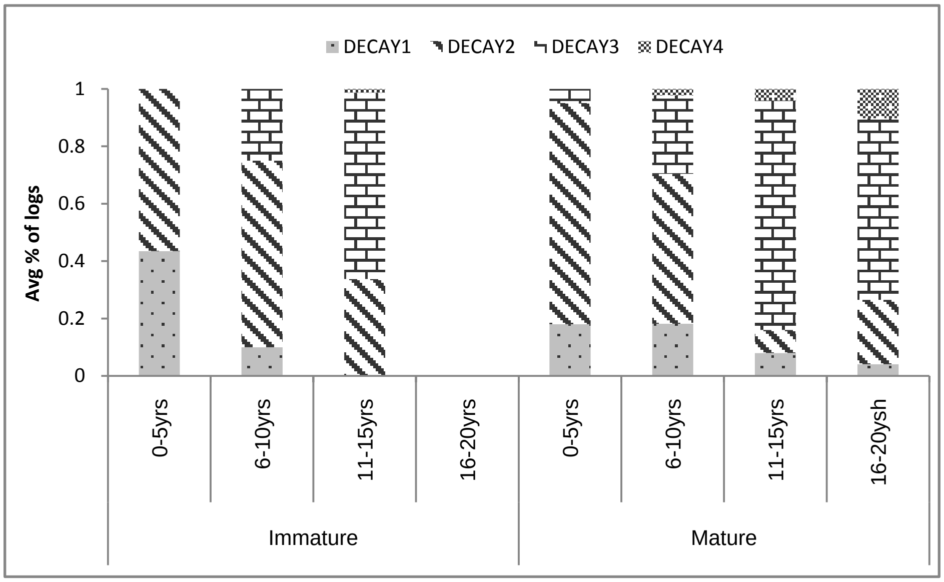


Fig 4.24 Average percent of logs by decay class (1-4) by YSH (0-5, 6-10, 11-15, 16-20yrs) and stand maturity (mature and immature) at Bamfield.

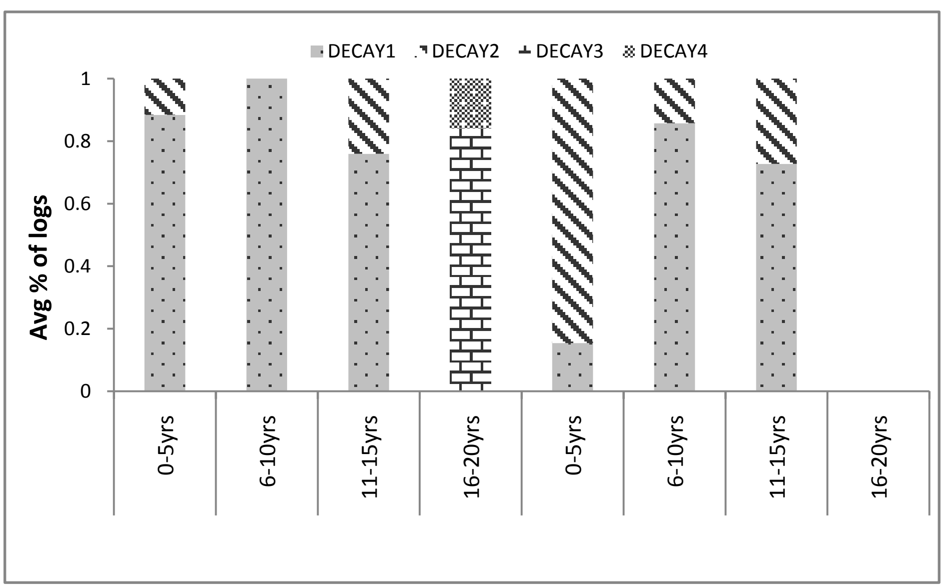


Fig 4.25 Average percent of logs among decay classes (1-4) by YSH (0-5, 6-10, 11-15, 16-20yrs) and stand maturity (mature and immature) at Port McNeill.

There was a significant difference in the number of recently downed trees (Decay class 1) between location (p= 0.0041), stand maturity (p= 0.0026) and years since harvest (p= 0.0354)

(Table 4.3). The number of trees in decay class 1 decreased substantially with increase in buffer age in immature stands in Bamfield (Fig 4.26). In Port McNeill this distinct pattern was the opposite. There was not any significant difference in average number of logs in decay class 2 (Fig 4.27). However, there was a significant difference in the number of decayed logs (decay class 3 and 4) in location (p= <.0001), years since harvest (p=<.0001) and location maturity interaction. The average number of decayed logs tended to increase with increase in buffer age (Fig 4.28).

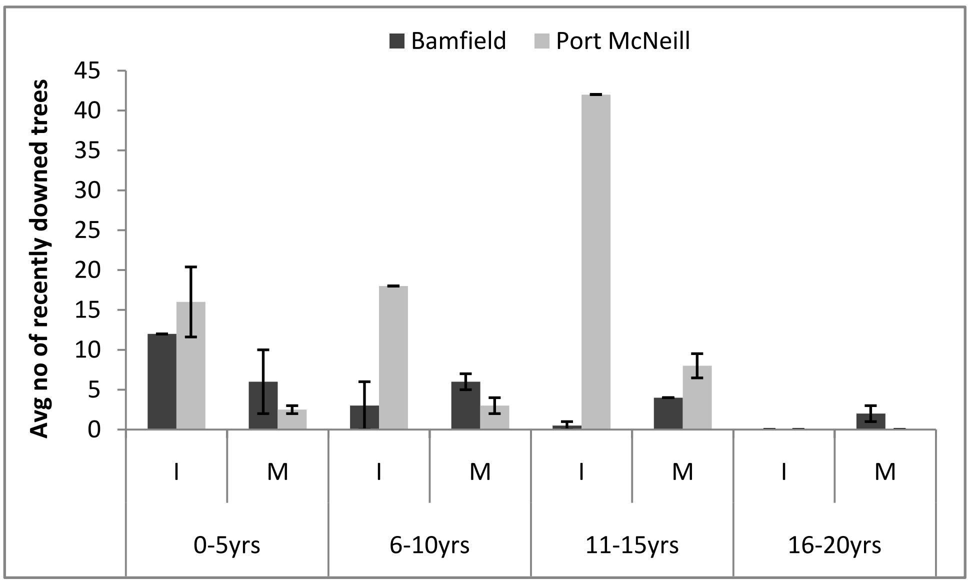


Fig 4.26 Average number of recently windthrown trees (decay class 1) by location (Bamfield and Port McNeill), stand maturity (Immature and mature) and year since harvest (0-5. 6-10, 11-16, 16-20 years) with SE bars.

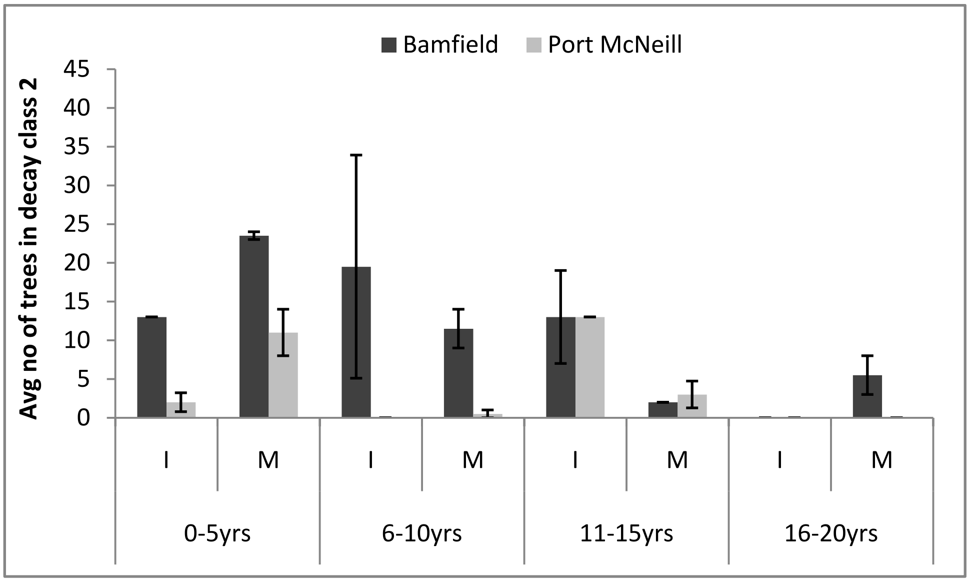


Fig 4.27 Average number logs (decay class 2) by location (Bamfield and Port McNeill), stand maturity (Immature and mature) and year since harvest (0-5. 6-10, 11-16, 16-20 years) with SE bars.

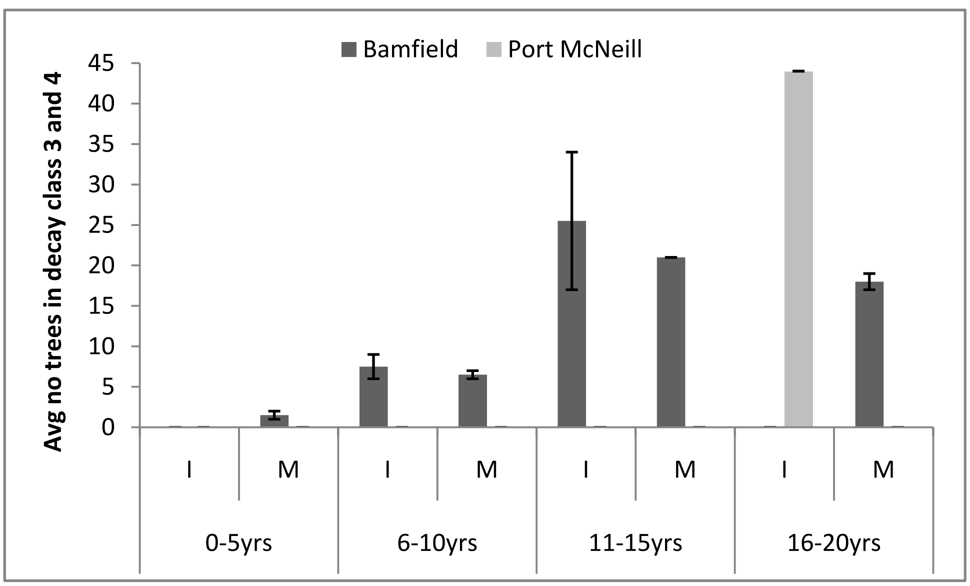


Fig 4.28 Average number higher decayed logs (decay class 3 and 4) by location (Bamfield and Port McNeill), stand maturity (Immature and mature) and year since harvest (0-5. 6-10, 11-16, 16-20 years) with SE bars.

The average length of log tended to decrease with increased decay (Fig 4.29). There was not a remarkable difference in decay condition of in-creek and spanning logs for newer buffers but the difference became more prominent as the buffer age increased. A higher percent of logs in-creek are in decay class 3 and 4 in buffers exposed for 16-20 years (Fig 4.30).

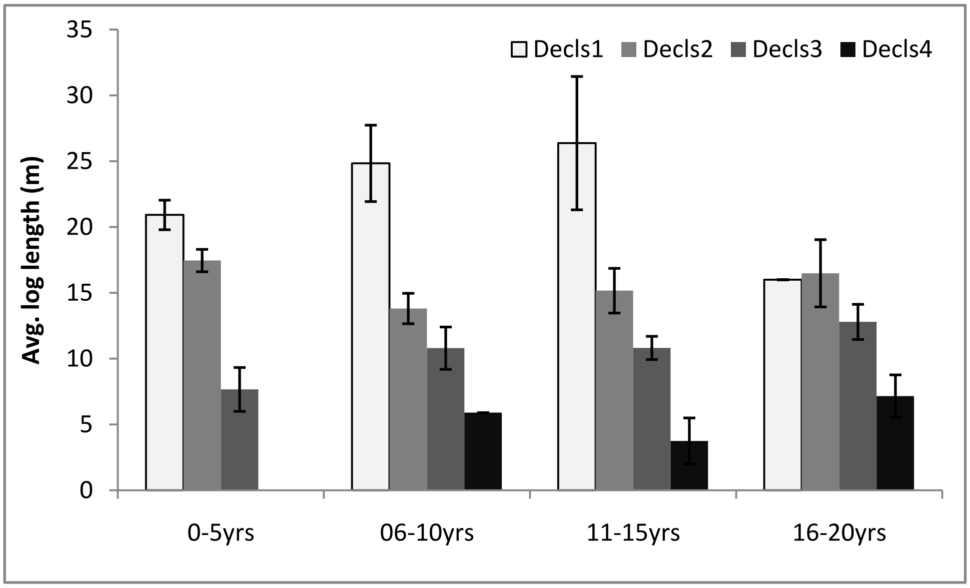


Fig 4.29 Average length of the log (m) by decay classes and years since harvest.

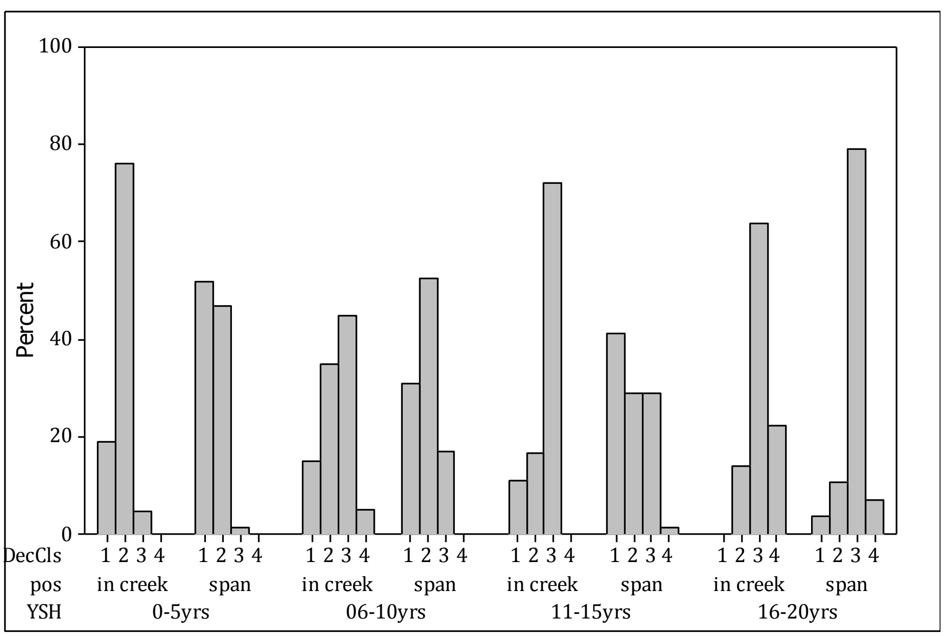


Fig 4.30 Percent of logs (within level of position and YSH) by position (in-creek and spanning) and years since harvest (YSH) for all locations.

4.4 Discussion

As in the Malcolm Knapp Research Forest (MKRF), a large proportion of logs spanned the creek in both locations on Vancouver Island. Even after 20 years following harvest, more than half of the logs were still spanning. While there are a number of studies that have investigated spanning logs (Grizzel and Wolf 1998, Wei 2005 a, Chen *et al*. 2006, Powell 2006, Jones and Daniels 2007), the lag time between the spanning condition and the actual recruitment of a log into a stream channel has not been documented. Working in montane forests in Alberta, Jones and Daniels (2007) anticipated a delay of 30-45 years before newly recruited logs contribute to stream morphology and function. While suspended, logs do not contribute much to the structure of aquatic ecosystems (Grizzel and Wolf 1998); however the vegetation growing on long term suspended logs could provide shade to the stream, and act as a source of leaf litter. The invertebrates living on logs could act as a food for fish in the stream, when they drop in the creek. Once the log is in the creek then it starts trapping sediments (Swanson and Lienkaemper 1978), and modifying channel morphology, creating debris jams and pools (Bisson *et al*. 1987) which in turn helps enhance fish habitat. Woody debris also acts as a source of long term nutrient loading (Wei *et al*. 1997). However, logs that enter the stream in an advanced state of decay would not be expected to persist in the channel for as long as less decayed material. Short lengths of decayed material were observed piling up in debris jams, indicating that even small streams carry material away during peak flows. LWD loads in streams depend on how long the debris is entrained within the channel. LWD may reside in channels for decades to centuries or move unhindered downstream (Naiman *et al*. 2002). It is possible that some pieces of LWD remain in channels for several centuries to millennia (Hyatt and Naiman 2001, Murphy and Koski 1989).

Taking a retrospective approach helped me to compare the condition of logs over time and I found the height above stream of logs slowly decreased with time since harvest. Jones and Daniels (2007) cross-dated spanning and in-creek logs and found the time since death of spanning logs to be less than logs in other positions such as partial bridge, loose or buried. This clearly indicates as time progresses the position of logs also changes. Jones and Daniels (2007) found time since death of LWD increased with progressive decay class. I found the lengths of logs to be shorter for higher decay classes. Similar results were reported by Powell (2006) and by Jones and Daniels (2007). There is an increase in decay class of in-creek and spanning logs in older buffers. However, a large proportion of in-creek logs were in decay class 3 and 4. Since logs immersed in water decay more slowly, it makes sense that the path by which logs enter the stream channel, and the decay condition of the logs when they enter the water will make a difference to long term condition and residency of the logs in-creek.

The majority of logs are oriented diagonal or perpendicular to the stream direction, with just 4% of logs oriented parallel to the stream. Studies by Chen *et al*. 2006, Wei (2005 b), Hauer *et al*. (1999) also reported logs were most likely to be oriented perpendicular to the stream. Richmond and Faush (1995) reported that the proportion of logs perpendicular to stream is less in large streams than smaller ones. In contrast with small channels, LWD in intermediate sized channels was orientated parallel to stream flow, indicating that LWD has moved and re-orientated (Chen *et al*. 2006). LWD in larger streams is more likely to come from debris torrenting and from bank erosion (Nakamura and Swanson 1993), and it is possible that these mechanisms introduce material into stream channels in less advanced state of decay than in the case of windthrown spanning logs. This is a question that warrants further investigation.

It is a general observation that riparian buffers are more suspectible to windthrow in the first few winters following harvesting (Miquelajauregui 2008, Rollerston and McGourlick 2001, Liquori 2006). The number of recent windthrown trees decreased substantially with increase in buffer age in Bamfield, and spanning logs were more decayed in older buffers. In contrast, in Port McNeill this pattern was not apparent, likely due to periodic addition of new windthrow trees. Interestingly the logs in decay class 3 and 4 were present only in the older buffer age class (16-20yrs) in Port McNeill, indicating the rate of decay to be slower than at Bamfield. The average summer temperature shows Port McNeill to be cooler and have less precipitation than Bamfield which might be the reason for slow decaying of logs in Port McNeill. This is one of the limitations in using the retrospective approach to evaluate log decay rates; however, it also points to the complexity of the LWD recruitment process in buffers.

Riparian forest buffers are most susceptible to windthrow in the first few years after harvest of the adjacent forest because the most vulnerable trees fall and the remaining trees become more windfirm through time (Weidman 1920, Gratkowski 1956, Steinblums *et al*. 1984). In addition, post harvest windthrow may reduce the stand density of trees to the extent that the competition mortality in the stand is reduced and thus also the LWD recruitment in stream (Liquori 2006). This effect should be more pronounced in younger, high density stands where stem exclusion is still occurring. Overall the average number of logs was higher in immature stands than mature ones. The average number of small (7.5-20cm) and medium sized (20-40) spanning logs was higher in immature stands in both locations. On the other hand, LWD loads have been reported to increase with stand age (e.g. Bilby and Ward 1991, Spies *et al*. 1988). In this study I measured only post harvest windthrow and so it is possible that the older streams included more long term LWD.

4.5 Conclusion

Significant quantities of LWD continue spanning the creek up to 20 years following the pulse of post harvest windthrow in buffers exposed by harvesting in coastal BC. There is clearly a substantial lag time between windfall and the actual recruitment of LWD in the creek. Along with differences in the proportion of spanning vs in-creek LWD, the average LWD height above stream tends to decrease as buffers age. The height above stream is negatively correlated with decay class and buffer age and positively correlated with orientation (0 - 90°) of tree relative to stream. Because of their higher density, immature stands produce more spanning logs than mature stands for a similar level of windthrow. Furthermore, a large proportion of LWD is from small trees than big ones. Windthrow is oriented, with the majority of logs falling perpendicular to the stream flow direction. Trees that fall parallel to the stream are more likely to become entrained in the channel while relatively undecayed, and may persist longer since decay in water is suppressed. This issue needs further investigation.

5. Synthesis, Conclusions and Recommendations.

In two of the three locations, MKRF and Bamfield, post harvest windthrow resulted in a pulse of LWD recruitment in the riparian buffer zone. However, most windthrown logs were suspended well above the bank-full height of the stream. The buffer in MKRF was exposed for 8 years and in Vancouver Island for 0-20 years. But even in the oldest buffer age class more than half of the logs were still spanning. The condition of spanning logs changed with time. The height for the suspended logs above bank-full height gradually decreased and they decay. As decay progresses logs break into shorter lengths, and log height above the stream decreased. Field observations indicate that the logs were more likely to decay and break at the upper end where they contact the soil, rather than at the mid-point. Log height above stream was greater where logs were oriented perpendicular to the stream, and at both MKRF and Vancouver Island, trees were more likely to lie perpendicular to stream direction than parallel to it. In older buffers, the average log diameter at mid creek was greater. This indicates that smaller logs were decaying more quickly.

Mature stands experience less windthrow than immature even in unharvested stands. There is more recent windthrow in the 70 year old stand than in the 130 year old and old growth stands in MKRF. The pattern of post-harvest windthrow was similar between the 70 year old stand at MKRF (Miquelajauregui 2008) and the stands at Bamfield on Vancouver Island. In both cases, the level of new windthrow decreased with time since harvest. This is consistent with other studies. This pattern was less apparent in the stands at Port McNeill, perhaps because of recent stronger than normal wind activity. While windthrow is the dominant source of post-harvest mortality and log recruitment in riparian buffers, competition induced mortality also plays a role, particularly in the younger, denser stands.

The percentage of in-creek logs gradually increased with the buffer age. In-creek logs were in a more advanced state of decay than spanning logs at both MKRF and Vancouver Island locations. Many logs in an advanced stage of decay were still spanning the creek and with increasing decay the log lengths are getting shorter. It seems likely that those spanning logs will end up in the creek in short lengths and in a very decayed condition that cannot persist in the stream or play much of a role in structuring channel sediments. If this is the case then very few of the spanning logs will serve as long term LWD in creek. From a windthrow management and buffer design perspective, post-harvest windthrow appears to place little LWD in the stream in the short term. Windthrown logs will gradually recruit into the stream over a period of several decades, with smaller logs of deciduous and other rapidly decaying species entering first. The contribution of these well decayed logs to the aquatic ecosystem should be further investigated.

To account for the time taken for spanning logs to recruit into the creek channel, there is a need for some extra components in LWD recruitment models. There are a number of LWD recruitment models, including AQUAWOOD (Wei 2005 b), RAIS (Welty *et al*. 2002), STREAMWOOD (Meleason 2001), and CWD (Bragg *et al*. 2000). All these models are comprised of two sub models. The first model calculates the mortality of trees in the stands and the second model is the wood model for which the output of first model is the input. These existing LWD recruitment models do not differentiate between spanning vs in-creek logs. The models give the LWD recruitment into the stream; however, the role of the geometry of the LWD and stream valley profile is not well thought-out. For estimating the time for spanning logs to come in the creek, the geometry of logs plays an important role. Windthrow, which is the dominant source of LWD in many buffers, is not considered as a cause for tree mortality except in RAIS (Welty *et al*. 2002). These knowledge and modeling gaps can be filled.

One of the key findings of this research is the lag time for spanning logs to enter the creek. In order to address this obvious knowledge gap, it is necessary to represent the geometry and condition of spanning LWD, and to introduce a decay function for change in condition over time. The retrospective approach on Vancouver Island enabled me to understand the change over time in suspended height, and the decay pattern of windthrown logs. This information can be used to build a conceptual model for recruitment of spanning LWD, to examine the appropriate functional form for model components like decay functions, and to provide approximate decay rates by species and size group. The proposed architecture of this conceptual model is in Fig 5.1. Initial programming has been completed by Tim Shannon and Steve Mitchell, and the following is a synopsis of model components and calculations.

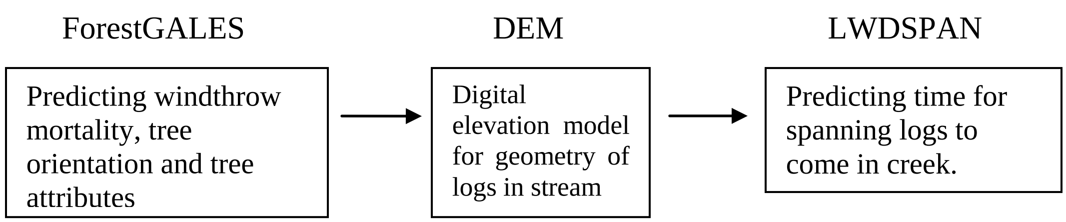


Fig 5.1 Architecture of LWDSPAN windthrow recruitment model.

ForestGALES is a computer based windthrow process model in which the wind speed at which a tree will uproot or break (critical wind speed), and the probability of the critical wind speed occurring in a given year, are calculated for trees growing within stands under various management regimes in a particular geographic/topographic location (Gardiner *et al*. 2000). ForestGALES_BC is launched from WindFIRM (Byrne *et al*. unpublished) which is also programmed in Python. WindFIRM creates a spatial framework for calculations with tree lists provided by the user based on plot information, or supplied by a forest growth and yield model such as TASS. WindFIRM, calculates neighbourhood level stand variables for 25m*25m pixels and passes this information to ForestGALES_BC for tree-level calculations of wind loading and resistance. The tree list is passed back from ForestGALES_BC with an additional field that indicates whether the tree has survived or failed for the specified above canopy wind speed and direction. Since the tree list can be derived from plot or growth models, it would also be possible to specify which trees die and subsequently fail due to competition mortality. LWDSPAN determines the probable break points for a log when it hits the ground by estimating the cumulative turning moment and sectional resistive moments for any stem segments that are suspended above the ground. The LWDSPAN output graphics include plan views of the terrain model and buffer location with locations and orientations of windthrown trees (Figs 5.2 and 5.3), and profile views of windthrown trees and stream valley profiles (Fig 5.4 and Appendix 10). In these profile graphics, the tree is shown in 1m sections in the top of the image, and below that the position of the tree after it hits the ground is shown along with the ground profile. The numbers of the sections where the tree makes contact with the ground are also given in this image.

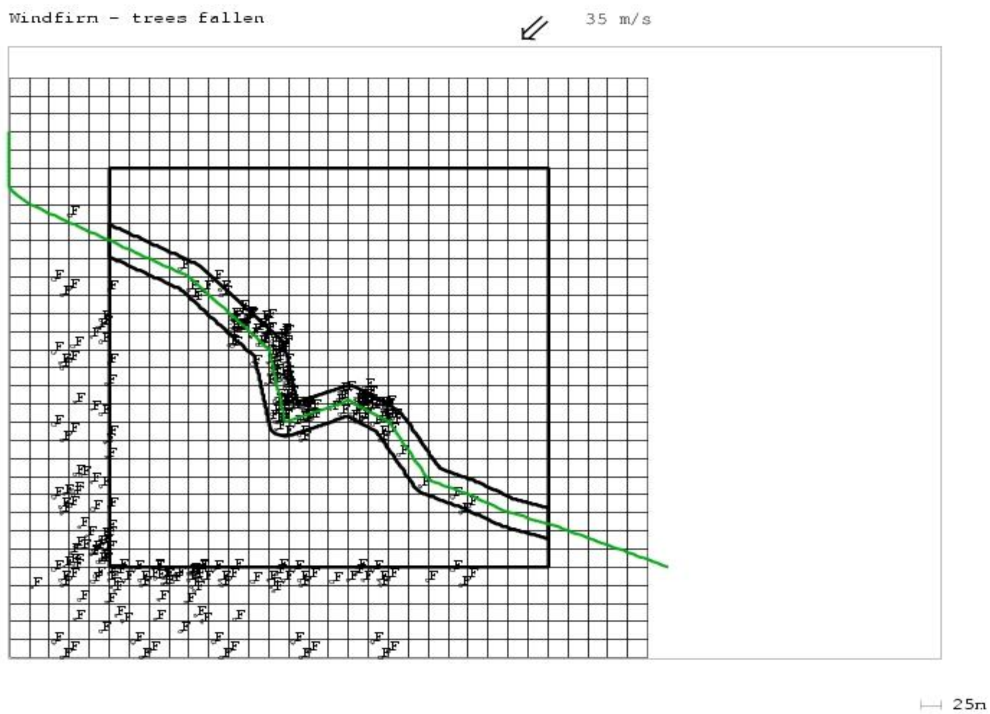


Fig 5.2 Graphics showing plan view of stream, buffer and cutblock boundries showing locations of windthrow trees (marked with F for ‘fallen’). Provided by Tim Shannon

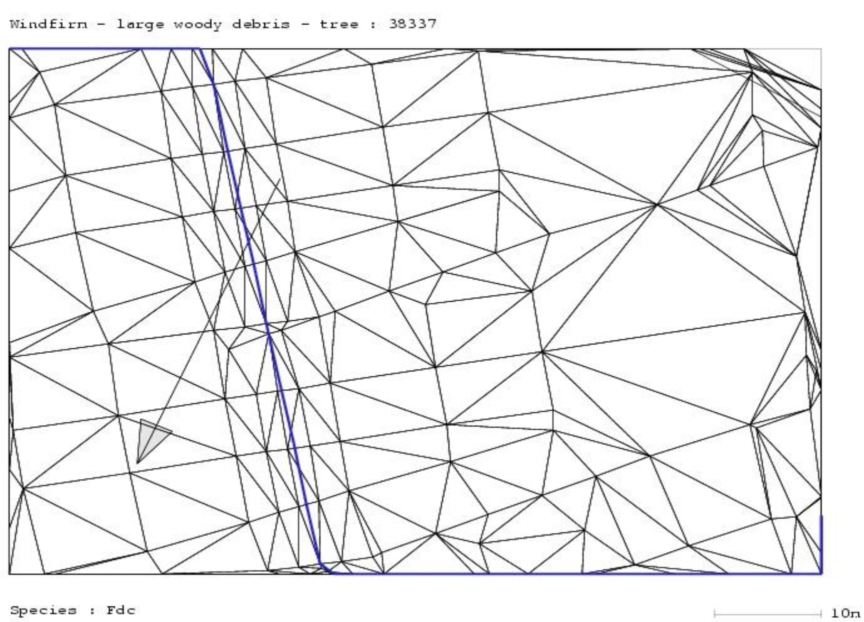


Fig 5.3 Triangular irregular network (TIN) in plan view showing terrain and stream location. Provided by Tim Shannon.

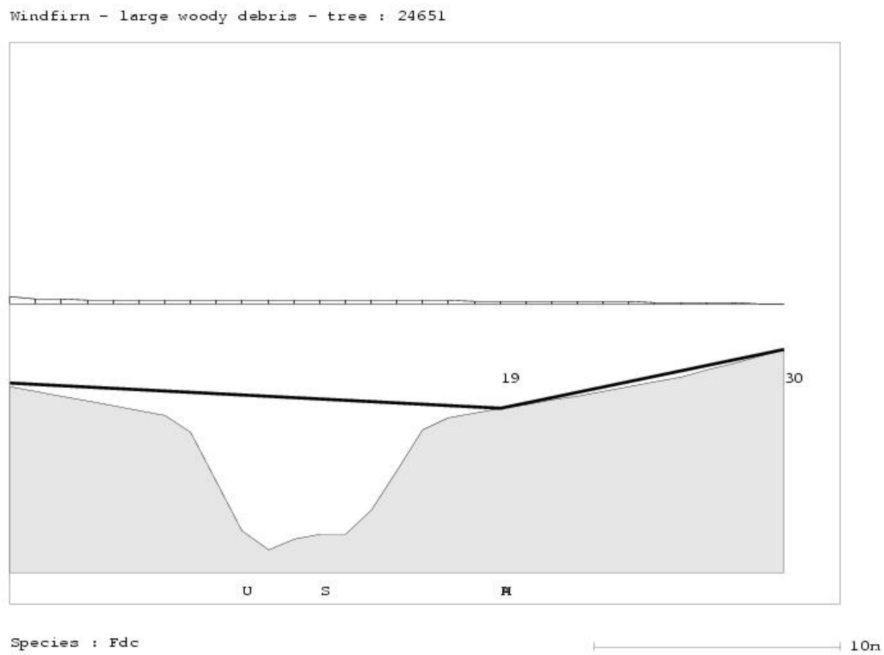


Fig 5.4 Output from LWDSPAN module of WindFIRM. (U is the unsupported segment of log, S is the stream and M is the break point when log hit the ground). Complete log is divided into a meter section with log breakage at 19m. Provided by Tim Shannon.

By integrating the ForestGALES_BC tree characteristics and windthrow orientation results with a digital elevation model (DEM), we can realistically describe the initial geometry of the logs following a windthrow event. Once the tree is on the ground the LWDSPAN model then runs through annual time steps using a simple exponential decay function with species specific decay coefficients. These decay coefficients of species are discussed in Chapter 2, and can be refined based on empirical results from retrospective analyses such as the Vancouver Island study. However, rather than reducing stem mass as in traditional decay models, the LWDSPAN function reduces the effective diameter of the stem. In each time step, the load and resistance of the unsuspended section is calculated using simple beam theory. When the self-load exceeds the resistance, the section fails and new suspension points are determined. This process repeats until the log within the active channel width has broken into sections of 1m or less (full decay). For each tree, the number of years to this stage is noted. The output tree list includes all of the tree level input information plus the number of years to full decay, or time for spanning logs to come into the creek. The resulting set of integrated models (TASS, WindFIRM, ForestGALES_BC and LWDSPAN) will enable users to evaluate the potential consequences of windthrow in riparian buffers and test different cutblock and buffer design scenarios.

There remain a number of questions for further investigation, and areas for model refinement. These include long term monitoring of spanning logs in the creek to check how the condition of logs changes over time. I found the logs enter the creek in decayed condition, so the residency time of these decayed logs in the creek should be explored. The other interesting thing will be to monitor the pattern of sectional decay of spanning logs, since in my fieldwork I observed that logs decayed faster in the sections directly in contact with the ground. A simple approach to answer these questions would be to put logs in various positions and stage of decay above and within the stream channel and monitor the change in status and condition of logs over time. This would enable us to better understand the mechanisms behind the recruitment and subsequent in-stream residency of windthrown LWD over time.

References

Alban, D. H., and J. Pastor. 1993. Decomposition of aspen, spruce, and pine boles on two sites in Minnesota. Canadian Journal of Forest Research 23, : 1744-9.

Anderson, N. H., J. R. Sedell, M. L. Roberts, and F. J. Triska. 1978. The role of aquatic invertebrates in processing wood debris in coniferous forest streams. American Midland Naturalist 100, : 64-82.

Arnborg, T. 1942. Lågaföryngringen i en syd-lappländsk granurskog. Sv. Skogsvårdsför. Tidsk. 40: 47-78.

Bartels, R., J. D. Dell, R. L. Knight and G. Schaefer. 1985. Dead and down woody material. In: Management of wildlife and fish habitats in forests in western Oregon and Washington. E.R. Brown (ed.). USDA For. Serv. Pub. No. R6-FoWL-192. Portland, Oregon. 171-186.

Basham, J. T. 1951. The pathological deterioration of balsam fir killed by the spruce budworm. Pulp Pap. Mag. Can. 52,: 120-134.

BC Ministry of Forests. 1995. Riparian Management Area Guidebook. Victoria, BC.

Beechie, T. J., and T. H. Sibley. 1997. Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams. Transactions of the American Fisheries Society 126, (2): 217-29.

Beese, B., B. Bilby, M. Bothwell, , J. Heffner, D. Hogan, D. Lynch, J. Richardson, J. Sleeman, and P. Tschaplinski. 2003. Variable retention and the conservation of small streams and their riparian areas. Forestry Innovation Investment.

Benda, L. E., and J. C. Sias. 2003. A quantitative framework for evaluating the mass balance of in-stream organic debris. Forest Ecology and Management 172, (1): 1-16.

Berg, N., A. Carlson, and D. Azuma. 1998. Function and dynamics of woody debris in stream reaches in the Central Sierra Nevada, California. Canadian Journal of Fisheries and Aquatic Sciences 55, (8): 1807-20.

Bilby, R. E., J. T. Heffner, B. R. Fransen, J. W. Ward, and P. A. Bisson. 1999. Effects of immersion in water on deterioration of wood from five species of trees used for habitat enhancement projects. North American Journal of Fisheries Management 19, (3): 687-95.

Bilby, R.E. and J.W. Ward. 1991.Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and 2nd growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences 48, 2499-2508.

Bilby, R.E. and J.W.Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in Western Washington. Trans. Am. Fisheries Society 118, 368–378

Bisson, P. A., R. E. Bibly, M. D. Bryant, C. A. Dolloff, G. B. Grette, R. A. House, M. L. Murphy, K. V. Koski, and J. R. Sedell. 1987. Large woody debris in forested streams in Pacific Northwest: past, present and future. In: E. O. Salo, T. W. Cundy (Ed). Streamside management: forestry and fisheries interactions. Contribution No. 57, Seattle, WA: Institute of Forest Resources, University of Washington; 143-190.

Bisson, P.A., and R. E. Bilby. 1998. Organic matter and trophic dynamics. Pages 373-398 *In* R.J. Naiman and R.E. Bilby,eds. River ecology and management: lessons from the Pacific coastal ecoregion. Springer-Verlag, New York.

Bragg, D. C., J. L. Kershner, and D. W. Roberts. 2000. Modeling large woody debris recruitment for small streams of the central rocky mountains. General Technical Report - Rocky Mountain Research Station, USDA Forest Service(-): ii + 36.

Brosofske, K. D., Chen JiQuan, R. J. Naiman, and J. F. Franklin. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. Ecological Applications 7, (4): 1188-200.

Brown, G.W. 1969. Predicting temperature of small streams. Water Resour. Res 5: 68-75.

Brown, S., Mo JiangMing, J. K. McPherson, and D. T. Bell. 1996. Decomposition of woody debris in western Australian forests. Canadian Journal of Forest Research 26, (6): 954-66.

Bryne, K. E., T. Shannon, S.J. Mitchell (unpublished). WindFIRM (Wind Forest Instability Risk Model) Reference manual.

Bull, E. L. 1983. Longevity of snags and their use by woodpeckers. In Snag habitat Management (J. W. Davis, G. A. Goodwin, and R. A. Ockenfels, ed.), 64-67. USDA For. Serv. Gen. Tech. Rep. RM-99. Rocky Mt. For. Range Exp. Stn., Fort Collins, Colarado.

Busse, M. D. 1994. Downed bole-wood decomposition in lodgepole pine forests of central Oregon. Soil Science Society of America Journal 58, : 221-7.

Chambers, J. Q., J. P. Schimel, and A. D. Nobre. 2001. Respiration from coarse wood litter in central Amazon forests. Biogeochemistry 52, (2): 115-31.

Chen, X. Y., X. H. Wei, and R. Scherer. 2005. Influence of wildfire and harvest on biomass, carbon pool, and decomposition of large woody debris in forested streams of southern interior British Columbia. Forest Ecology and Management 208, (1): 101-14.

Chen, X.Y., X. H. Wei, R. Scherer, C. Luider, and W. Darlington. 2006. A watershed scale assessment of in-stream large woody debris patterns in the southern interior of British Columbia. Forest Ecology and Management 229, (1): 50-62.

Christensen, O. 1977. Estimation of standing crop and turnover of dead wood in a Danish oak forest. Oiko 28: 177-186.

Christy, E. J., and R. N. Mack. 1984. Variation in demography of juvenile T*suga heterophylla* across the substratum mosaic. Journal of Ecology, UK 72, : 75-91.

Cleverly, J.R., J. R. Thibault, J. Pearce, and C. N. Dahm. 2000. Evapotranspiration from Middle Rio Grande (New Mexico) riparian ecosystems:role of flooding and community composition. Ecological Society of America 85thAnnual Meeting.

Cline, S. P., A. B. Berg, and H. M. Wight. 1980. Snag characteristics and dynamics in douglas-fir forests, western Oregon. Journal of Wildlife Management 44, (4): 773-86.

Daniels, L. D., J. Dobry, K. Klinka, and M. C. Feller. 1997. Determining year of death of logs and snags of thuja plicata in southwestern coastal British Columbia. Canadian Journal of Forest Research 27, (7): 1132-41.

De Groot, J. D., S. C. Hinch, and J. S. Richardson. 2007. Effects of logging second-growth forests on headwater populations of coastal cutthroat trout: A 6-year, multistream, before-and-after field experiment. Transactions of the American Fisheries Society. 136,: 211- 226.

DeLong, S. C., L. D. Daniels, B. Heemskerk, and K. O. Storaunet. 2005. Temporal development of decaying log habitats in wet spruce-fir stands in east-central British Columbia. Canadian Journal of Forest Research 35, (12): 2841-50.

Densmore, N., J. Parminter, and V. Stevens. 2005. Coarse woody debris: Inventory, decay modelling, and management implications in three biogeoclimatic zones. BC Journal of Ecosystems and Management 5, (04): 14-29.

Edmonds, R. L., and A. Eglitis. 1989. The role of the douglas-fir beetle and wood borers in the decomposition of and nutrient release from Douglas-fir logs. Canadian Journal of Forest Research 19, : 853-9.

Enrong Y., W. Xihua, and H. Jianjun. 2006. Concept and classification of coarse woody debris in forest ecosystems. Front. Biol. China 1: 76-84 (in Chinese).

Erickson, H. E., R. L. Edmonds, and C. E. Peterson. 1985. Decomposition of logging residues in Douglas-fir, western hemlock, pacific silver fir, and ponderosa pine ecosystems. Canadian Journal of Forest Research 15, : 914-21.

Everett, R., J. Lehmkuhl, R. Schellhaas, P. Ohlson, D. Keenum, H. Riesterer, and D. Spurbeck. 1999. Snag dynamics in a chronosequence of 26 wildfires on the east slope of the Cascade range in Washington state, USA. International Journal of Wildland Fire 9, (4): 223-34.

Fahey, T. J. 1983. Nutrient dynamics of aboveground detritus in lodgepole pine (*Pinus contorta ssp. latifolia*) ecosystems, southeastern Wyoming. Ecological Monographs 53, : 51-72.

Fausch, K.D., T. G. Northcote. 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. Canadian Journal of Fisheries and Aquatic Sciences 49: 682-693.

Feller, M. C. 2003. Coarse woody debris in the old-growth forests of British Columbia; old-growth forests in Canada. Environ. Rev. 11 (suppl 1): S135- S157.

Feller, M. C., R. Lehmann, and P. Olanski. 2000. Influence of forest harvesting intensity on nutrient leaching in southwestern British Columbia. Journal of Sustainable Forestry, 10, 241-247.

Feller, M., and P. Sanders. 1999. The origins of the Maple Ridge Research Forest riparian-stream ecosystem study In: Ecology and management of riparian-stream ecosystems: A large scale experiment at The University of British Columbia Malcolm Knapp Research Forest. Proceedings of a workshop held at the University of British Columbia Vancouver, B.C.

Fetherston, K. L., R. J. Naiman, and R. E. Bilby. 1995. Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest; special issue. biogeomorphology, terrestrial and freshwater ecosystems: Proceedings of the 26th binghampton symposium in geomorphology, held October 6-8, 1995. Geomorphology 13, (1): 133-44.

Fogel R., M. Ogawa, and J. M. Trappe. (unpublished). Terrestial decomposition a synopsis. Internal Report 135, Coniferous forest biome, Corvallis, OR.

Foster, J. R., and G. E. Lang. 1982. Decomposition of red spruce and balsam fir boles in the white mountains of New Hampshire. Canadian Journal of Forest Research 12, : 617-26.

Ganey, J. L. 1999. Snag density and composition of snag populations on two national forests in Northern Arizona. Forest Ecology and Management 117, (1): 169-78.

Gardiner, B., H. Peltola, and S. Kellomäki. 2000. Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. Ecological Modelling 129, (1): 1-23.

Golladay, S. W., and J. R. Webster. 1988. Effects of clear-cut logging on wood breakdown in Appalachian mountain streams. American Midland Naturalist 119, (1): 143-55.

Governor Salmon Recovery Office, Washington State. Glossary. Website accessed on 18/12/2007. URL www.governor.wa.gov/gsro/glossary/default.asp

Graham, R. L. 1982. Biomass dynamics of dead Douglas-fir and western hemlock boles in mid elevation forests of the Cascade Range. Ph.D. thesis, Oregon State Univ., Corvallis.

Graham, R. L., and K. Cromack Jr. 1982. Mass, nutrient content and decay rate of dead boles in rain forests of Olympic national park. Canadian Journal of Forest Research 12, : 511-21.

Gratowski, H. J. 1956. Windthrow around staggered settings in old growth Douglas-fir. Forest Science 2: 60-74.

Green, R.N., K. Klinka. 1994. A field guide to site identification and interpretation for the Vancouver Forest Region. Min. For., Victoria, BC, Land Manage. Handbook no 28.

Gregory, S., F. J. Swanson, A. W. McKee, and K. W. Cummins. 1991. An ecosystem perspective of riparian zones. BioScience, 41, 540-551.

Grette, G. B.1985. The role of large organic debris in juvenile salmonid rearing habitat in small streams. M.Sc. thesis, University of Washington, Seattle, Wash.

Grier, C. C. 1978. A tsuga heterophylla-picea sitchensis ecosystem of coastal Oregon: Decomposition and nutrient balances of fallen logs. Canadian Journal of Forest Research 8, : 198-206.

Grizzel, J. D., and N. Wolff. 1998. Occurrence of windthrow in forest buffer strips and its effect on small streams in Northwest Washington. Northwest Science 72, (3): 214-27.

Gurnell, A. M., and R. Sweet. 1998. The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. Earth Surface Processes and Landforms 23, (12): 1101-21.

Hairston-Strang, A. B., and P. W. Adams. 1998. Potential large woody debris sources in riparian buffers after harvesting in Oregon, U.S.A. Forest Ecology and Management 112, (1): 67-77.

Harmon, M. E., D. F. Whigham, J. Sexton, and I. Olmsted. 1995. Decomposition and mass of woody detritus in the dry tropical forests of the northeastern Yucatan peninsula, mexico. Biotropica 27, (3): 305-16.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, et al. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15, : 133-302.

Harmon, M. E., K. Cromack Jr., and B. G. Smith. 1987. Coarse woody debris in mixed-conifer forests, sequoia national park, California. Canadian Journal of Forest Research 17, (1): 1265-72.

Harmon, M. E., O. N. Krankina, and J. Sexton. 2000. Decomposition vectors: A new approach to estimating woody detritus decomposition dynamics. Canadian Journal of Forest Research 30, : 76-84.

Hauer, F. R., G. C. Poole, J. T. Gangemi, and C. V. Baxter. 1999. Large woody debris in bull trout (*Salvelinus confluentus*) spawning streams of logged and wilderness watersheds in northwest Montana. Canadian Journal of Fisheries and Aquatic Sciences 56, (6): 915-24.

Hedman, C. W., D. H. van Lear, and W. T. Swank. 1996. In-stream large woody debris loading and riparian forest seral stage associations in the southern Appalachian mountains. Canadian Journal of Forest Research 26, (7): 1218-27.

Helfield, J. M., and R. J. Naiman. 2001. Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity. Ecology 82, (9): 2403-9.

Hennon, P. E., C. G. Shaw, and E. M. Hansen. 1990. Dating decline and mortality of chamaecyparis nootkatensis in southeast Alaska. Forest Science 36, (3): 502-15.

Hofgaard, A. 1993. Structure and regeneration patterns in a virgin *Picea abies* forest in northern Sweden. Journal of Vegetation Science 4, : 601-8.

Hyatt, T. L., and R. J. Naiman. 2001. The residence time of large woody debris in the queets river, Washington, USA. Ecological Applications 11, : 191-202.

Idol, T. W., P. E. Pope., R. A. Figler and F. Ponder. 1999. Characterization of coarse woody debris across a 100 year chronosequence of upland oak-hickory forests; Proceedings, 12th central hardwood forest conference; 1999 February 28 March 1-2; Lexington, Ky. Gen. Tech. Rep. SRS-24. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 293p.

Idol, T. W., R. A. Figler, P. E. Pope, and F. Ponder. 2001. Characterization of coarse woody debris across a 100 year chronosequence of upland oak-hickory forests. Forest Ecology and Management 149, (1-3) (AUG 1): 153-61.

Ingles, L. G. 1933. The succession of insects in tree trunks as shown by the collection from various stages of decay. Jour. Ent. And Zool. 25: 57-59.

Jenkins, M. A., and G. R. Parker. 1997. Changes in down dead wood volume across a chronosequence of silvicultural openings in southern Indiana forests; 11th central hardwood forest conference. proceedings of a meeting held at the university of Missouri, Columbia, MO, march 23-26, 1997. General Technical Report - North Central Forest Experiment Station, USDA Forest Service: 162-9.

Jenny, H., S. P. Gessel, and F. T. Bingham. 1949. Comparative study of decomposition rates of organic matter in temperature and tropical regions. Soil Science 68, : 419-32.

Johnson, A.C., D.N. Swanston, and K.E.McGee. 2000. Landslide initiation, runout, and deposition within clearcuts, and old-growth forests of Alaska. Journal of American Water Resources Association 36:17-30.

Johnson, E. A., and D. F. Greene. 1991. A method for studying dead bole dynamics in *Pinus-contorta var latifolia - Picea-engelmannii* forests. Journal of Vegetation Science 2, (4): 523-30.

Jones, T.A., and L. D. Daniels. Dynamics of large woody debris in small streams disturbed by the 2001 Dogrib fire in the Alberta foothills. Forest Ecology and Management 256: 1751-1759.

Jonsson, B. G. 2000. Availability of coarse woody debris in a boreal old-growth P*icea abies* forest. Journal of Vegetation Science 11, (1) (FEB): 51-6.

Kiffney, P. M., J. P. Bull, and M. C. Feller. 2002. Climatic and hydrologic variability in a coastal watershed of southwestern British Columbia. Journal of the American Water Resources Association. 38,: 1437-1451.

Kozlowski, T. T., P. J. Kramer, and S. G. Pallardy. 1991. The physiological ecology of woody plants. San Diego, California; USA: Academic Press, Inc.

Krankina, O. N., and M. E. Harmon. 1995. Dynamics of the dead wood carbon pool in northwestern russian boreal forests; boreal forests and global change: Peer-reviewed manuscripts selected from the international boreal forest research assocation conference, held in Saskatoon, Saskatchewan, Canada, september 25-30, 1994. Water, Air, and Soil Pollution 82, (1): 227-38.

Krankina, O. N., M. E. Harmon, and A. V. Griazkin. 1999. Nutrient stores and dynamics of woody detritus in a boreal forest: modeling potential implications at the stand level. Canadian Journal of Forest Research 29:20-32.

Kreutzweiser, D. P., K. P. Good, and T. M. Sutton. 2005. Large woody debris characteristics and contributions to pool formation in forest streams of the boreal shield. Canadian Journal of Forest Research 35, (5): 1213-23.

Laiho, R., and C. E. Prescott. 1999. The contribution of coarse woody debris to carbon, nitrogen, and phosphorus cycles in three rocky mountain coniferous forests. Canadian Journal of Forest Research 29, (1): 1592-603.

Laiho, R., and C. E. Prescott. 2004. Decay and nutrient dynamics of coarse woody debris in northern coniferous forests: A synthesis. Canadian Journal of Forest Research 34, : 763-77.

Lambert, R. L., G. E. Lang, and W. A. Reiners. 1980. Loss of mass and chemical change in decaying boles of a subalpine balsam fir forest. Ecology 61, : 1460-72.

Lamberti G. A., and S. V. Gregory. 1996. Transport and retention of CPOM. *In*: Methods is stream ecology. F. R. Hauer and G. A. Lamberti (Ed.), Academic press, San Diego, California, USA. 217-229.

Lanquaye-Opoku, N., and S. J. Mitchell. 2005. Portability of stand-level empirical windthrow risk models. Forest Ecology and Management 216, (1): 134-48.

Lee, P. C., S. Crites, M. Nietfeld, Hai Van Nguyen, and J. B. Stelfox. 1997. Characteristics and origins of deadwood material in aspen-dominated boreal forests. Ecological Applications 7, : 691-701.

Lewis, J. 1998. Evaluating the impacts of logging activities on erosion and suspended sediment transport in the Caspar Creek Watersheds. USDA Forest Service Gen. Tech. Rep. PSW-GTR-168.

Lienkaemper, G. W., and F. J. Swanson. 1987. Dynamics of large woody debris in streams in old growth Douglas-fir forests. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 17, (2) (FEB): 150-6.

Lindenmayer, D. B., R. D. Incoll, R. B. Cunningham, and C. F. Donnelly. 1999. Attributes of logs on the floor of Australian mountain ash (*Eucalyptus regnans*) forests of different ages. Forest Ecology and Management 123, (2-3) (NOV 8): 195-203.

Liquori, M. K. 2006. Post-harvest riparian buffer response: Implications for wood recruitment modeling and buffer design; riparian ecosystems and buffers - multiscale structure, function and management. American water resources association summer specialty conference, Olympic valley, California, USA,; june 2004.

Liquori, M., and C. R. Jackson. 2001. Channel response from shrub dominated riparian communities and associated effects on salmonid habitat. Journal of the American Water Resources Association 37, (6): 1639-51.

Long, B.A., 1987. Recruitment and abundance of large woody debris in an Oregon coastal stream system. M.S. Thesis. Oregon State University, Corvallis, OR

Macdonald, J. S., P. G. Beaudry, E. A. MacIsaac, and H. E. Herunter. 2003. The effects of forest harvesting and best management practices on streamflow and suspended sediment concentrations during snowmelt in headwater streams in sub-boreal forests of British Columbia, Canada; small stream channels and their riparian zones: Their form, function and ecological importance in a watershed context. Vancouver, British Columbia, Canada, 19-21 February 2002.

Mackensen, J., J. Bauhus, E. Webber. 2003. Decomposition rates of coarse woody debris- A review with particular emphasis on Australian tree species. Australian Journal of Botany 51, : 27-37.

MacMillan, P. C. 1988. Decomposition of coarse woody debris in an old-growth Indiana forest. Canadian Journal of Forest Research 18, (1): 1353-62.

Martin, D. J., and L. E. Benda. 2001. Patterns of instream wood recruitment and transport at the watershed scale. Transactions of the American Fisheries Society 130, (5): 940-58.

Martin, D. J., and R. A. Grotefendt. 2007. Stand mortality in buffer strips and the supply of woody debris to streams in southeast Alaska. Canadian Journal of Forest Research 37, (1): 36-49.

Maser, C., and J. M. Trappe. 1984. The seen and unseen world of the fallen tree. 1984. General Technical Report, Pacific Northwest Forest and Range Experiment Station, USDA Forest Service: ii + 56.

Maser, C., R. Anderson, K. Cromack Jr., J. T. Williams and R. E. Martin. 1979. Dead woody material. *In* J. W. Thomas (ed.) Wildlife habitats in managed forests. Chapt 6. USDA For. Serv. Agri. HAndb 553. Washington Off., Washington D. C.

Mattson, K. G., and W. T. Swank. 1984. Carbon dioxide fluxes from conventional and whole tree harvested watershed-effects of wood residue. Bulletin of the Ecological Society of America 65, 123.

McCullough, H. A. 1948. Plant succession on fallen logs in a virgin Spruce/Fir forest. Ecology 29, : 508-513.

McDade, M. H., F. J. Swanson, W. A. McKee, J. F. Franklin, and J. van Sickle. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research 20, (3): 326-30.

McDade, M.H., F. J. Swanson, W. A. McKee, J. F. Franklin, and J. V. Sickle. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research **20:** 326-330.

McHenry, M. L., E. Shott, R. H. Conrad, and G. B. Grette. 1998. Changes in the quantity and characteristics of large woody debris in streams of the olympic peninsula, Washington, U.S.A. (1982-1993). Canadian Journal of Fisheries and Aquatic Sciences 55, (6): 1395-407.

Means, J. E., K. Cromack Jr., and P. C. MacMillan. 1985. Comparison of decomposition models using wood density of Douglas-fir logs. Canadian Journal of Forest Research 15, : 1092-8.

Means, J. E., P. C. MacMillan, and K. Cromack Jr. 1992. Biomass and nutrient content of Douglas-fir logs and other detrital pools in an old-growth forest, Oregon, USA. Canadian Journal of Forest Research 22, (1): 1536-46.

Meleason, M. A., S. V. Gregory, and J. P. Bolte. 2003. Implications of riparian management strategies on wood in streams of the Pacific northwest. Ecological Applications 13, (5): 1212-21.

Meleason, M.A. 2001. A simulation model of woody dynamics in Pacific Northwest streams. Ph.D Dissertation, OSU, Corvallis, Oregon, USA.

Melillo, J. M., R. J. Naiman, J. D. Aber & K. N. Eshleman, 1983. The influence of substrate quality and stream size on wood decomposition dynamics. Oecologia 58: 281–285.

Mielke, J. L. 1950. Rate of deterioration of beetle-killed engelmann spruce. Journal of Forestry 48, (12): 882-8.

Minderman, G. 1968. Addition, decomposition and accumulation of organic matter in forests. Journal of Ecology 56, : 355-62.

Ministry of Environment B.C. Glossary. Web site accessed on 18/12/2007. URL. www.env.gov.bc.ca/wld/documents/wrp/wrt6/glossary.html

Ministry of Forest and Range (MOFR) 2007. Vegetation resources inventory. Ground sampling procedures.Version 4.7 MOFR Forest Analysis and Inventory Branch for the terrestrial Ecosystems Task Force Resources Information Standards Committee.

Ministry of Forest. B.C. Glossary of forestry terms. Web site accessed on 18/12/2007. URL http://www.for.gov.bc.ca/hfd/library/documents/glossary/1990s/L.htm

Miquelajauregui, Y. 2008. Vegetation community development in small stream buffers eight years after harvesting at Malcolm Knapp Research Forest. MSc Thesis, The University of British Columbia, Vancouver BC.

Montes, F., and I. Cañellas. 2006. Modelling coarse woody debris dynamics in even-aged Scots pine forests. Forest Ecology and Management 221, (1): 220-32.

Moore, K., K. Jones, and J. Dambacher 2002. Methods for stream habitat surveys. Oregon Department of Fish and Wildlife. Aquatic Inventories Project. Natural Production Program. Version 12.1, Corvallis, OR, 97333.

Moore, R. D., D. L. Spittlehouse, and A. Story. 2005. Riparian microclimate and stream temperature response to forest harvesting: A review. Journal of the American Water Resources Association 41, (4): 813-34.

Morrison, M. L., and M. G. Raphael. 1993. Modeling the dynamics of snags. Ecological Applications 3, (2): 322-30.

Murphy, M. L., and K V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management 9, : 427-436.

Naesset, E. 1999. Decomposition rate constants of *Picea abies* logs in southeastern Norway. Canadian Journal of Forest Research 29, : 372-81.

Naesset, E. 1999. Relationship between relative wood density of picea abies logs and simple classification systems of decayed coarse woody debris. Scandinavian Journal of Forest Research 14, : 454-61.

Naiman, R. J., and R. E. Bilby. Eds. 1998. River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. New York: Springer-verlag.

Naiman, R. J., E. V. Balian, K. K. Batrz, R. E. Bilby, and J. J. Latterell. 2002. Dead wood dynamics in stream ecosystems.USDA Forest Service Gen. Tech. Rep. PSW-GTR-181.

Nakamura, F., and F. J. Swanson. 1993. Effects of coarse woody debris on morphology and sediment storage of mountain stream system in western Oregon. Earth Surf. Processes Landforms, 18:43-61.

Newberry, J. E., K. J. Lewis, and M. B. Walters. 2004. Estimating time since death of *Picea glauca x P. engelmannii* and *Abies lasiocarpa* in wet cool sub-boreal spruce forest in east-central British Columbia. Canadian Journal of Forest Research 34, (4): 931-8.

Oliver, C. D., and B. C. Larson. 1990. Forest stand dynamics. New York; USA: McGraw-Hill, Inc.

Olson, J. S. 1963. Energy storage & the balance of producers & decomposers in ecological systems. Ecology 44, : 322-31.

Opperman, J. J. 2005. Large woody debris and land management in California's hardwood-dominated watersheds. Environmental Management 35, (3): 266-77.

Pedlar, J. H., J. L. Pearce, L. A. Venier, and D. W. McKenney. 2002. Coarse woody debris in relation to disturbance and forest type in boreal Canada. Forest Ecology and Management 158, (1): 189-94.

Powell, S.R. 2006. A wood inventory and dendroecological analysis of large woody debris in small streams in the Foothills Model Forest, Hinton, Alberta. M.Sc. Thesis, University of British Columbia, Vancouver, BC.

Progar, R. A., T. D. Schowalter, C. M. Freitag, and J. J. Morrell. 2000. Respiration from coarse woody debris as affected by moisture and saprotroph functional diversity in western Oregon. Oecologia 124, (3): 426-31.

Pyle, C., and M. M. Brown. 1999. Heterogeneity of wood decay classes within hardwood logs; understanding change in managed and unmanaged forests. first biennial north American forest ecology workshop, raleigh, N.C., USA, 24-26 june, 1997. Forest Ecology and Management 114, (2): 253-9.

Raphael, M. G., and M. L. Morrison. 1987. Decay and dynamics of snags in the Sierra Nevada, California. Forest Science 33, (3): 774-83.

Raphael, M. G., and M. White. 1984. Use of snags by cavity-nesting birds in the Sierra Nevada. Wildl. Monogr. 86:1-66.

Rayner, A. D. M., and N. K. Todd. 1979. Population and community structure and dynamics of fungi in decaying wood. Advances in Botanical Research 7, : 333-420.

Richmond, A. D., and K. D. Fausch. 1995. Characteristics and function of large woody debris in subalpine rocky mountain streams in northern Colorado. Canadian Journal of Fisheries and Aquatic Sciences 52, (8): 1789-802.

Robison, E. G., and R. L. Beschta. 1990. Characteristics of coarse woody debris for several coastal streams of southeast Alaska, USA. Canadian Journal of Fisheries and Aquatic Sciences 47, : 1684-93.

Rollerson, T. P. and K. McGourlick 2001. Riparian windthrow – northern Vancouver Island. In: Proceedings of the Windthrow Researchers Workshop, Richmond BC Jan. 31-Feb 1, 2001. Compiled by S.J. Mitchell and J. Rodney. pp. 139-156.

Sampson, G. R., and T. L. Wurtz. 1994. Record interior Alaska snowfall effect on tree breakage. Northern Journal of Applied Forestry 11, (4): 138-40.

Scherer, R. 2004. Decomposition and longevity of in-stream woody debris: a review of literature from North America. Pp 127-133 In G. L. Scrimgeour, G. Eisler, B. McCulloch, U. Silins and M.

Monita. (Ed). Forest Land- Fish Conference II- Ecosystem Stewardship through collaboration. Proc. Forest-Land-Fish Conf. II, April 26-28, Edmonton, Alberta.

Scott, R. E., and S. J. Mitchell. 2005. Empirical modelling of windthrow risk in partially harvested stands using tree, neighbourhood, and stand attributes. Forest Ecology and Management 218, (1): 193-209.

Sickle, J. van, and S. V. Gregory. 1990. Modeling inputs of large woody debris to streams from falling trees. Canadian Journal of Forest Research 20, (10): 1593-601.

Siitonen, J., P. Martikainen, P. Punttila, and J. Rauh. 2000. Coarse woody debris and stand characteristics in mature managed and old-growth boreal mesic forests in southern Finland. Forest Ecology and Management 128, (3) (APR 1): 211-25.

Simon, A., and A. J. C. Collison. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27, (5): 527-46.

Söderström, L. 1988. Sequence of bryophytes and lichens in relation to substrate variables of decaying coniferous wood in northern Sweden. Nordic Journal of Botany 8, : 89-97.

Soderstrom, L. 1989. Regional distribution patterns of bryophyte species on spruce logs in northern Sweden. Bryologist 92, (3) (FAL): 349-55.

Sollins, P. 1982. Input and decay of coarse woody debris in coniferous stands in western Oregon and Washington. Canadian Journal of Forest Research 12, : 18-28.

Sollins, P., S. P. Cline, T. Verhoeven, D. Sachs, and G. Spycher. 1987. Patterns of log decay in old-growth Douglas-fir forests. Canadian Journal of Forest Research 17, (1): 1585-95.

Spies, T. A., J. F. Franklin, and T. B. Thomas. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology 69, : 1689-702.

Steinblums, I. J., H. A. Froehlich, and J. K. Lyons. 1984. Designing stable buffer strips for stream protection. Journal of Forestry 82, (1): 49-52.

Stewart, G. H., and L. E. Burrows. 1994. Coarse woody debris in old-growth temperate beech (nothofagus) forests of New Zealand. Canadian Journal of Forest Research 24, (1): 1989-96.

Stone, J. N., A. MacKinnon, J. V. Parminter, and K. P. Lertzman. 1998. Coarse woody debris decomposition documented over 65 years on southern Vancouver Island. Canadian Journal of Forest Research 28, : 788-93.

Storaunet, K. O., and J. Rolstad. 2002. Time since death and fall of Norway spruce logs in old-growth and selectively cut boreal forest. Canadian Journal of Forest Research 32, (10): 1801-12.

Swanson, F. J., and G. W. Lienkaemper. 1978. Physical consequences of large organic debris in Pacific northwest streams.

Swanson, F. J., G. W. Lienkaemper, and J. R. Sedell. 1976. History, physical effects and management implications of large organic debris in western oregon streams.

Swift, M. J. 1973. The estimation of mycelia biomass by determination of the hexoamine content of wood tissue decayed by fungi. Soil Biology and Biochemistry 5, 321-332

Swift, M. J., O. W. Heal, and J. M. Anderson. 1979. Decomposition in terrestrial ecosystems.

Takahashi, M., Y. Sakai, R. Ootomo, and M. Shiozaki. 2000. Establishment of tree seedlings and water-soluble nutrients in coarse woody debris in an old-growth picea-abies forest in hokkaido, northern japan. Canadian Journal of Forest Research 30, : 1148-55.

Thomas, J. W. 1979. Wildlife habitats in managed forests in the Blue Mountains of Oregon and Washington. Agri. Handb. 553. Washington D.C. Department of Agriculture, Forest Service.

Thomas, J. W., R. J. Miller, H. Black, J. E. Rodiek, and C. Maser. 1976. Guidelines for maintaining and enhancing wildlife habitat in forest management in the blue mountains of Oregon and

Washington; transactions, forty-first North American wildlife and natural resources conference, march 21-25, 1976, Washington, D.C.

Triska, F. J., and K. Cromack Jr. 1980. The role of wood debris in forests and streams, ed. R. H. Waring. Corvallis, Oregon; USA: Oregon State University Press.

Tyrrell, L. E., and T. R. Crow. 1994. Dynamics of dead wood in old-growth hemlock-hardwood forests of northern Wisconsin and northern Michigan. Canadian Journal of Forest Research 24, : 1672-83.

Ursitti, V.L. 1990. Riparian vegetation and abundance of woody debris in streams of Southwestern Oregon. M.S. Thesis. Oregon State University. Corvallis, OR, p. 89

Vanderwel, M. C., J. R. Malcolm, and S. M. Smith. 2006. An integrated model for snag and downed woody debris decay class transitions. Forest Ecology and Management 234, (1): 48-59.

Wallace, J. B., J. R. Webster, S. L. Eggert, J. L. Meyer, and E. R. Siler. 2001. Large woody debris in a headwater stream: Long-term legacies of forest disturbance; plant litter processing in freshwater. 2nd meeting of the plant litter processing in freshwater group, Lunz/See, austria, september 1999.

Wang, X. L., K. Klinka, H. Y. H. Chen, and L. De Montigny 2002. Root structure of western hemlock and western redcedar in single-and mixed-species stands. Canadian Journal of Forest Research, 32,997-1004.

Wei, X. 2004. Quantification of the difference in In-stream woody debris loads between harvesting and wildfire disturbance in the interior of BC (Section 2). [Online] http://www.for.gov.bc.ca/hfd/library/FIA/2004/FSP_R04-051a.pdf

Wei, X. 2005(a). Instream large woody debris as a sustainability indicator at watershed scales for headwater streams of the BC Interior, BC Ministry of Forest Library. Annual Technical Report 2005.

Wei, X. 2005(b). Simulation of large woody debris recruitment and dynamics associated with wildfire disturbance and harvesting in headwater streams of the BC Interior. Annual Technical Report 2004 / 2005 FSP project number Y051107.

Wei, X., J. P. Kimmins, K. Peel, and O. Steen. 1997. Mass and nutrients in woody debris in harvested and wildfire-killed lodgepole pine forests in the central interior of British Columbia. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 27, (2) (FEB): 148-55.

Weidman, R. H. 1920. A study of windfall loss of western yellow pine in selection cuttings fifty to thirty years old.J.For.18:616-622.

Welty, J. J., T. Beechie, K. Sullivan, D. M. Hyink, R. E. Bilby, C. Andrus, and G. Pess. 2002. Riparian aquatic interaction simulator (RAIS): A model of riparian forest dynamics for the generation of large woody debris and shade. Forest Ecology and Management 162, (2): 299-318.

Wieder, R. K., and G. E. Lang. 1982. A critique of the analytical methods used in examining decomposition data obtained from litter bags. Ecology 63, : 1636-42.

Woldendrop, G., R. J. Keenan, and M. F. Ryan. 2002. Coarse woody debris in Australian forest ecosystems. A report for the National Greenhouse Strategy, Module 6.6 (Criteria and Indicators of Sustainable Forest Mangement), April, 2002.

Appendix 1- Description of variables

Variable	Label	Description
Channel form	ChFrm	A category to classify the channel as narrow or broad based on valley width index.
Narrow channel type	CB	Constrained by bedrock
	CH	Constrained by hill slope
	CF	Constrained by alluvial fan
Broad channel type	US	Unconstrained predominantly single channel
	UA	Unconstrained Anastomosing several complex interconnecting channels
	UB	Unconstrained Braided channel (numerous, small channels often flowing over alluvial deposits)
	CT	Constraining terrace
	CA	Constrained by alternating terraces
	CL	Constrained by land use
Valley form	VFrm	General description of the valley cross section with emphasis on the configuration of valley floor and classify into narrow or broad based on valley width index.
Narrow valley type	SV	Steep V-shaped valley or bed rock gorge (side slope≥ 60°)
	MV	Moderate V-shaped valley (side slope >30°, <60°)
	OV	Open V-shaped valley (side slope ≤ 30°)
		Constraining terraces. Terraces high and close to active channel.
Broad valley type	CT	Multiple terraces. Surface with varying height and distance from
	MT	the channel.
		Wide active flood plain. Significant portion of valley floor
	WF	influenced by annual floods.
Active channel	ACW	Distance along channel at bankfull flow
Valley floor	VFW	Distance of valley along channel.
Value width index	VWI	It is a ratio of VFW divided by ACW.
Distance along	Dist_along	Distance of log from point of commencement
Status		SL: Standing Live, LL: Live leaning, DB:Dead broken, SD: Standing dead, DL: Dead leaning, UR: Uprooted
Species	Spp	Hw: western hemlock, Cw: western red cedar, Fd: Douglas-fir, Ss: Sitka spruce, Ep: Paper birch, Dr: red alder, Mb: Maple
Decay class	Decls	Classification system for logs based on decay. Bartel *et al* 1985

Orientation	Brg	Orientation to the top of log and orientation of stream measured with compass in degrees.
Diameter at breast height	DBH	Diameter at breast height measured with diameter tape.
Active channel width length	ACWL	The portion of log in active channel measured with tape.
Total length	TL	The total length of log.
Debris type		RN: Rotwad attached to ends, N:Broken ends, C:Cut ends
Base diameter	Base_dia	Diameter at base of the downed logs.
Length midcreek	Len_midcreek	Distance of log from mid creek to the base of the tree.
Span length	Span_leng	Distance between two suspending points of log.
Height above stream	HAS	Height of log from bankfull height of creek.
Log angle		The inclination of log measured with Suntos in percent.
Years since harvest	YSH	The buffer age class 0-5yrs, 6-10yrs, 11-15yrs, and 16-20yrs.

Appendix 2- Summary of variables

MKRF

Variables	Label	Mean	Std. Dev	Min	Max
		Stand Variables			
Diameter (70yrs) (cm)	DBH	24	14.5	7.5	90.4
Diameter (130yrs) (cm)	DBH	45.5	37.6	7.5	221.5
Diameter (OG) (cm)	DBH	40.8	46.6	7.5	203
		Tree Variables			
Diameter at breast height (cm)	DBH	22.1	13.3	8	83
Total length (m)	TL	15.5	9.5	0.91	48.5
		Log Variables			
Base diameter (cm)	Base dia	22.6	14.5	4.7	120
Diameter at mid creek (cm)	DMC	16.6	9.3	7.5	68
Top diameter (cm)	Top dia	7.9	6.8	0.5	40
Length mid creek (m)	Len midcreek	5.9	4.9	0	30
Span length (cm)	span_length	7.9	5.3	0.5	32
Log length (m)	log_length	12.6	9.0	0.5	42.4
Height above stream (cm)	HAS	94.7	71.7	0	350
		Reach Variables			
Active channel width (m)	ACW	2.5	1.43	0.7	9.3
Valley floor width (m)	VFW	10.5	8.8	3.3	50

Vancouver Island

Variables	Label	Mean	Std. Dev	Min	Max
		Stand Variable			
Diameter at breast height (Immature stand) (cm)	DBH	34.4	20.1	7.5	156
Diameter at breast height (Mature stand) (cm)	DBH	37.9	32.0	7.5	291
		Log Variables			
Diameter at mid creek(cm)	DMC	31.0	19.9	8	225
Log length (m)	log_length	14.4	9.3	0.4	50
Height above stream (cm)	HAS	110	124	0	1300
		Reach Variables			
Active channel width (m)	ACW	2.9	1.7	0.7	9.3
Valley floor width (m)	VFW	13.2	11.6	3.3	50
Gradient (%)	Gradnt	3.5	5	1	30

Appendix 3- Decay classifications for LWD/CWD

SN	Author and Year	Location	Species	No of classes	Attributes Considered	Logs / Snags	1st class include live /recently felled
1	McCullough 1948; modified from Ingles 1933 (as cited in 3)	Colorado	*Picea engelmannii* and *Abies lasiocarpa*	8	Bark, branches, outline (definite/indefinite)	Logs	Freshly fallen
2	Thomas 1979			5	Bark, structural integrity, branches	Logs	
3	Maser *et al*. 1979			5	Bark, twigs, texture, shape, color, portion on ground	Logs	
4	Triska and Cromack 1980* adapted from Fogel etal.			5			
5	Sollins 1982; modified from Fogel *et al*.	WOW	*Pseudotsuga menziesii*	5	Bark, structural integrity, branch systems, invading roots, vegetation	Logs	Freshly fallen
6	Graham and Cromack 1982; modified from Triska and Cromack 1980	Washington	*Tsuga heterophylla*	5	Bark, branch, sapwood and heartwood conditions	Logs	
7	Maser and Trappe 1984*; adapted from Fogel *et al*. (as cited in Takahashi *et al*. 2000)			5	Bark, twigs, texture, shape, wood color		
8	Christy and Mack 1984; from Sollins 1982	Central Oregon	*Tsuga heterophylla*	5	Percentage of log covered by bark, Structural integrity, log capable of supporting own weight, extent of log branch systems, distribution of invading roots, rooted vegetation.	Logs	

9	Grette 1985*			7	Bark, limbs, twigs, surface condition	Logs	
10	Sollins *et al*. 1987; from Fogel *et al*.	OW	*Pseudotsuga menziesii*	5	Bark, twigs, log supporting own weight, sapwood and heartwood decay	Logs	Freshly fallen
11	Murphy and Koski 1989	Alaska	*Tsuga heterophylla* and *Picea sitchensis*	7	Bark, limbs, twigs, surface condition	Logs	
12	Robinson and Beschta 1990; from Maser and Trappe 1984	Alaska	*Tsuga heterophylla*, *Picea sitchensis* and *Alnus rubra*	5	Bark, twigs, texture, shape, wood color	Logs	
13	Lee etal 1997	Alberta	Aspen dominated Boreal forest	7	Bark, twigs ,branch vegetation	Logs	
14	Jenkins and Parker 1997; from Triska and Cromack 1980	Southern Indiana	Fagus-*Acer saccharum*	5	Bark, structural integrity, branches	Logs	
15	Pyle and Brown 1999; from Maser *et al*. 1979	Connecticut	Hardwood forest	5	Bark, branch, shape and structure, wood color	Logs	
16	Hyatt and Naiman 2001	Washington	*Picea sitchensis*, *Pseudotsuga menziesii*, *Tsuga heterophylla* and black cotton wood	7	Bark, limbs, twigs, surface condition	Logs	
18	Pedlar *et al*. 2002	Ontaria	Boreal forest	3	Bark, percent of wood hard, structural integrity	Logs	
19	Feller 2003	BC		4	Bark, branches, wood color, shape	Logs	Recently felled
20	Vanderwel *et al*. 2006	Ontaria	*Pinus strobus*, *P resinosa* with red oak, white birch,	5	Bark, wood condition, texture, vegetation on logs	Logs (separate for snags)	

			spruce, balsam fir and red maple			
21	Enrong *et al*. 2006			5	Structural integrity, leaves, branches, bark, bole shape, wood consistency, color of wood, portion of log on ground, invaded by root, vegetation	Logs (separate for snags)
22	Fogel *et al*. (unpublished)*			5		
23	Spies *et al*. 1988;modified form Fogel *et al*. by Sollins 1982	WOW	*Pseudotsuga menziesii*	5	Bark, structural integrity, branch systems, invading roots, vegetation	Logs
24	Bartels *et al*. 1985 from Maser *et al*. 1979			5	Bark, twigs, texture, shape, color, portion on ground	Logs
25	Daniels *et al*. 1997	Coastal BC	*Thuja plicata*	5	Bark, twigs, texture, shape, color, portion on ground	Logs
26	Delong *et al*. 2005	BC	*Picea glauca, Abies lasiocarpa*	5	Structural integrity, soundness of sap and heart wood	
27	Newbery *et al*. 2004	BC		5	Structural integrity, soundness of sound.	
28	Wei 2004 modified from Robison and Beschta 1990.	South central BC	Lodgepole pine, Engelmann spruce, Subalpine fir	3	Bark, twigs, texture,shape, wood color	Logs
29	Powell 2006 from Maser *et al*. 1979	West central Alberta	Lodgepole pine and Spruce	4	Wood structural characteristics and integrity	Logs

*Original Paper not found cited in other papers.
WOW- Western Oregon and Washington , NS- Northern Sweden, BC- British Columbia,
OW- Oregon and Washington

Appendix 4- Decay rate constant of logs with decomposition model.

Species	Location	Decay constant (k/year)	Variable	Decay Model	Reference
Picea engelmannii	Alberta	0.0054 (20 yrs)*	density	Single exponential	Johnson and Greene 1991
	Alberta	0.0025 (65 yrs)	density	Single exponential	Johnson and Greene 1991
Picea glauca	Alberta	0.0271	mass	Single exponential	Laiho and Prescott 1999
	Minnesota	0.071	density	Single exponential	Alban and Pastor 1993
Picea sitchensis	Washington	0.0119	density	Linear, Exponential & Logarithmic	Graham and Cromack 1982
Pinus banksiana	Minnesota	0.042	density	Single exponential	Alban and Pastor 1993
Pinus contorta	Alberta	0.0507	mass	Single exponential	Laiho and Prescott 1999
	Oregon	0.027	density	Single exponential	Busse 1994
	Wyoming	0.016	density	Single exponential	Fahey 1983
	Alberta	0.0171 (25 yrs)	density	Single exponential	Johnson and Greene 1991
	Alberta	0.0299 (15 yrs)	density	Single exponential	Johnson and Greene 1991
	Alberta	0.0153 (20 yrs)	density	Single exponential	Johnson and Greene 1991
	Alberta	0.0045 (65 yrs)	density	Single exponential	Johnson and Greene 1991
	Alberta	0.0035 (80 yrs)	density	Single exponential	Johnson and Greene 1991

Pinus resinosa	Minnesota	0.055	density	Single exponential	Alban and Pastor 1993
Pseudotsuga menziesii	Oregon	0.007	density	Single & Multiple exponential	Means *et al*. 1985,1992
	Oregon and Wasington	0.028	density	General model	Sollins 1982
	Oregon and Wasington	0.01	density	Single exponential	Sollins *et al*. 1987
	Oregon and Wasington	0.029	density	Single exponential	Spies *et al*. 1988
	British Columbia	0.012-0.067	density	Single exponential	Stone *et al*. 1998
	Washington	0.05-0.026	density	Single exponential	Edmonds and Eglitis 1989
Thuja plicata	Oregon and Washington	0.009	density	Single exponential	Sollins *et al*. 1987
Tsuga canadensis	Wisconsin and Michigan	0.021 (60yrs)	density	Single exponential	Tyrrell and Crow 1994
Tsuga canadensis	Wisconsin and Michigan	0.012 (12 yrs)	density	Single exponential	Tyrrell and Crow 1994
Tsuga heterophylla	Oregon and Washington	0.016	density	Single exponential	Sollins *et al*. 1987
	Washington	0.01-0.023	density	Linear, Exponential & Logarithmic	Graham and Cromack 1982
	Oregon	0.0118	mass	Single exponential	Grier 1978

Appendix 5- Comparision of LWD recruitment models (Modified from Wei 2005 b)

Variables		RAIS	CWD	STREAMWOOD	AQUAWOOD
Model	Type	Stand-level-based riparian LWD recruitment and shade	Stands-level-based LWD recruitment post processor	Individual-based stochastic (spatially explicit)	Stream-reach based recruitment and in-stream process model
	Utility	Riparian LWD recruitment and shade	Riparian LWD recruitment	LWD recruitment and in stream dynamics	LWD recruitment and long term in-stream dynamic
	Scale	Reach level	Reach level	Reach to small basin	Reach
Sub model	Two sub model	Forest:ORGANON; Wood tracking model	Forest model: FVS; Wood model:CWD	Forest:gap models; Woodmodel	Forest: FORECAST, Wood model:Aquawoo d
Tree mortality	Mortality	Generation of dead trees per acre; allow only thinning option	A dead tree list from FSV; allow management options	A dead tree list per plot; allow management options	Determined by FORECAST
	Assumptions	Evenly distributed; dying tree will fall within the calendar year; fallen tree remain unbroken	Randomly distributed; consideration of snag residency and stem failure; allow LWD to break into pieces	Randomly distributed; dying trees will fall within the calendar year; allow breakage of dead trees	Dead trees must fall within 20yrs after death; allow breakage of tree
	Falling	Dying trees fall directionally	Dead trees fall in a tri model distribution	Dying trees fall directionally	Randomize falling direction in 8 separate zones
Recruitment representation	Compitition mortality	Yes	Yes	Yes	Yes
	Windthrow	Yes; assume a rate as fraction of live trees	No	No	No
	Bank erosion	No	No	No	Yes
	Upstream import	No; assume a steady-state condition	No; assume a steady-state condition	Yes	Yes

In-channel processes representation	Breakage	No	No	Yes	Yes
	Decay of depletion	Yes; using depletion for decay, breakage and transport	Yes	Yes	Yes
	Export or movement	No; assume steady-state condition	No; assume steady-state condition	Yes	Yes

Appendix 6- Pearson's correlations for variables (MKRF Buffer-width experiment)

	HAS	DMC	sqdmc	rtdmc	recidmc	logdmc	VWI	sqvwi	rtvwi	recivwi	logvwi	Deccls	Orientation
HAS	1.000	0.143	0.099	0.153	-0.133	0.154	-0.199	-0.146	-0.228	0.291	-0.255	-0.408	0.138
		0.017	0.098	0.011	0.026	0.010	0.001	0.018	0.000	<.0001	<.0001	<.0001	0.023
	283	279	279	279	279	279	266	266	266	266	266	278	274
DMC	0.143	1.000	0.940	0.986	-0.833	0.950	0.114	0.129	0.099	-0.033	0.079	-0.083	-0.061
	0.017		<.0001	<.0001	<.0001	<.0001	0.060	0.033	0.105	0.591	0.196	0.165	0.318
	279	287	287	287	287	287	272	272	272	272	272	279	274
sqdmc	0.099	0.940	1.000	0.874	-0.636	0.797	0.080	0.089	0.071	-0.030	0.059	-0.095	-0.082
	0.098	<.0001		<.0001	<.0001	<.0001	0.187	0.143	0.243	0.619	0.334	0.113	0.175
	279	287	287	287	287	287	272	272	272	272	272	279	274
rtdmc	0.153	0.986	0.874	1.000	-0.908	0.988	0.123	0.140	0.105	-0.031	0.083	-0.065	-0.053
	0.011	<.0001	<.0001		<.0001	<.0001	0.044	0.021	0.083	0.606	0.173	0.277	0.374
	279	287	287	287	287	287	272	272	272	272	272	279	274
recidmc	-0.133	-0.833	-0.636	-0.908	1.000	-0.960	-0.110	-0.130	-0.092	0.017	-0.069	-0.004	0.045
	0.026	<.0001	<.0001	<.0001		<.0001	0.070	0.033	0.129	0.782	0.256	0.944	0.461
	279	287	287	287	287	287	272	272	272	272	272	279	274
logdmc	0.154	0.950	0.797	0.988	-0.960	1.000	0.125	0.144	0.106	-0.028	0.083	-0.043	-0.049
	0.010	<.0001	<.0001	<.0001	<.0001		0.040	0.018	0.080	0.641	0.174	0.479	0.419
	279	287	287	287	287	287	272	272	272	272	272	279	274
VWI	-0.199	0.114	0.080	0.123	-0.110	0.125	1.000	0.967	0.989	-0.840	0.956	0.122	-0.066

	0.001	0.061	0.187	0.044	0.070	0.040		<.0001	<.0001	<.0001	<.0001	0.048	0.291
	266	272	272	272	272	272	274	274	274	274	274	266	259
sqvwi	-0.146	0.129	0.089	0.140	-0.130	0.144	0.967	1.000	0.920	-0.693	0.854	0.116	-0.057
	0.018	0.033	0.143	0.021	0.033	0.018	<.0001		<.0001	<.0001	<.0001	0.059	0.357
	266	272	272	272	272	272	274	274	274	274	274	266	259
rtvwi	-0.228	0.099	0.071	0.105	-0.092	0.106	0.989	0.920	1.000	-0.908	0.989	0.126	-0.061
	0.000	0.105	0.243	0.083	0.129	0.080	<.0001	<.0001		<.0001	<.0001	0.040	0.330
	266	272	272	272	272	272	274	274	274	274	274	266	259
recivwi	0.291	-0.033	-0.030	-0.031	0.017	-0.028	-0.840	-0.693	-0.908	1.000	-0.960	-0.133	0.007
	<.0001	0.591	0.619	0.606	0.782	0.641	<.0001	<.0001	<.0001		<.0001	0.030	0.910
	266	272	272	272	272	272	274	274	274	274	274	266	259
logvwi	-0.255	0.079	0.059	0.083	-0.069	0.083	0.956	0.854	0.989	-0.960	1.000	0.130	-0.048
	<.0001	0.196	0.334	0.173	0.256	0.174	<.0001	<.0001	<.0001	<.0001		0.034	0.441
	266	272	272	272	272	272	274	274	274	274	274	266	259
Deccls	-0.408	-0.083	-0.095	-0.065	-0.004	-0.043	0.122	0.116	0.126	-0.133	0.130	1.000	-0.075
	<.0001	0.165	0.113	0.277	0.944	0.479	0.048	0.059	0.040	0.030	0.034		0.220
	278	279	279	279	279	279	266	266	266	266	266	283	269
Orientation													1
													274

Where HAS is height above stream
DMC is diameter at mid creek and sqdmc, rtdms, recidmc, logdmc are various transformations of DMC.
VWI is valley width index and sqvwi, rtvwi, recivwi, logvwi are various transformations of VWI.
Deccls is Decay class of log ranging from 1-4.
Orientation is orientation of log relative to the stream flow.

Appendix 7- Pearson’s correlations for variables (MKRF Stand-age experiment)

	HAS	DMC	sqdmc	rtdmc	recidmc	logdmc	VWI	sqvwi	rtvwi	recivwi	logvwi	Deccls	Orientation
HAS	1.000	-0.127	-0.121	-0.122	0.082	-0.111	-0.073	-0.031	-0.126	0.290	-0.196	-0.424	0.242
		0.095	0.112	0.109	0.285	0.144	0.341	0.680	0.099	0.000	0.010	<.0001	0.001
		174	174	174	174	174	174	174	174	174	174	172	177
DMC		1.000	0.958	0.988	-0.849	0.955	0.349	0.300	0.361	-0.278	0.350	0.057	-0.242
			<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.000	<.0001	0.459	0.001
			175	175	175	175	175	175	175	175	175	172	177
sqdmc			1.000	0.905	-0.686	0.836	0.289	0.255	0.295	-0.226	0.283	0.021	-0.238
				<.0001	<.0001	<.0001	0.000	0.001	<.0001	0.003	0.000	0.782	0.001
				175	175	175	175	175	175	175	175	172	177
rtdmc				1.000	-0.917	0.989	0.360	0.304	0.376	-0.292	0.367	0.078	-0.239
					<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.309	0.001
					175	175	175	175	175	175	175	172	177
recidmc					1.000	-0.965	-0.321	-0.254	-0.348	0.282	-0.350	-0.134	0.210
						<.0001	<.0001	0.001	<.0001	0.000	<.0001	0.080	0.005
						175	175	175	175	175	175	172	177
logdmc						1.000	0.357	0.295	0.377	-0.297	0.372	0.099	-0.232
							<.0001	<.0001	<.0001	<.0001	<.0001	0.195	0.002
							175	175	175	175	175	172	177
VWI							1.000	0.941	0.969	-0.596	0.872	0.142	-0.045
								<.0001	<.0001	<.0001	<.0001	0.064	0.557
								175	175	175	175	172	170

sqvwi	1.000	0.833	-0.413	0.684	0.097	-0.064
		<.0001	<.0001	<.0001	0.208	0.410
		175	175	175	172	170
rtvwi		1.000	-0.736	0.963	0.173	-0.038
			<.0001	<.0001	0.023	0.626
			175	175	172	170
recivwi			1.000	-0.879	-0.232	0.050
				<.0001	0.002	0.516
				175	172	170
logvwi				1.000	0.207	-0.038
					0.007	0.622
					172	170
						-0.136
Deccls					1.000	0.074
						175
Orientation						1.000
						177

Where HAS is height above stream
DMC is diameter at mid creek and sqdmc, rtdms, recidmc, logdmc are various transformations of DMC.
VWI is valley width index and sqvwi, rtvwi, recivwi, logvwi are various transformations of VWI.
Deccls is Decay class of log ranging from 1-4.
Orientation is orientation of log relative to the stream flow

Appendix 8- Pearson’s correlations for variables (Port McNeill)

	HAS	DMC	sqdmc	rtdmc	recidmc	logdmc	VWI	sqvwi	rtvwi	recivwi	logvwi	DecCls	YSH	Orientation
HAS	1.000	0.146	0.117	0.160	-0.187	0.173	-0.077	-0.054	-0.098	0.162	-0.123	-0.441	-0.397	0.258
		0.011	0.043	0.006	0.001	0.003	0.184	0.356	0.089	0.005	0.033	<.0001	<.0001	0.002
	299	299	299	299	299	299	299	299	299	299	299	254	299	147
DMC	0.146	1.000	0.966	0.989	-0.794	0.955	0.367	0.338	0.361	-0.240	0.331	-0.147	-0.141	0.157
	0.011		<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.019	0.014	0.058
	299	301	301	301	301	301	301	301	301	301	301	256	301	147
sqdmc	0.117	0.966	1.000	0.921	-0.654	0.854	0.399	0.368	0.391	-0.255	0.357	-0.071	-0.095	0.144
	0.043	<.0001		<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.259	0.098	0.081
	299	301	301	301	301	301	301	301	301	301	301	256	301	147
rtdmc	0.160	0.989	0.921	1.000	-0.865	0.987	0.341	0.314	0.335	-0.223	0.307	-0.191	-0.166	0.160
	0.006	<.0001	<.0001		<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.002	0.004	0.053
	299	301	301	301	301	301	301	301	301	301	301	256	301	147
recidmc	-0.187	-0.794	-0.654	-0.865	1.000	-0.929	-0.221	-0.209	-0.213	0.132	-0.189	0.312	0.225	-0.140
	0.001	<.0001	<.0001	<.0001		<.0001	0.000	0.000	0.000	0.022	0.001	<.0001	<.0001	0.091
	299	301	301	301	301	301	301	301	301	301	301	256	301	147
logdmc	0.173	0.955	0.854	0.987	-0.929	1.000	0.307	0.285	0.301	-0.200	0.275	-0.236	-0.190	0.158
	0.003	<.0001	<.0001	<.0001	<.0001		<.0001	<.0001	<.0001	0.001	<.0001	0.000	0.001	0.055
	299	301	301	301	301	301	301	301	301	301	301	256	301	147
VWI	-0.077	0.367	0.399	0.341	-0.221	0.307	1.000	0.956	0.975	-0.655	0.891	-0.017	0.122	-0.032
	0.184	<.0001	<.0001	<.0001	0.000	<.0001		<.0001	<.0001	<.0001	<.0001	0.790	0.033	0.691
	299	301	301	301	301	301	308	308	308	308	308	256	308	154

sqvwi	-0.054	0.338	0.368	0.314	-0.209	0.285	0.956	1.000	0.869	-0.453	0.731	-0.047	0.143	-0.009
	0.356	<.0001	<.0001	<.0001	0.000	<.0001	<.0001		<.0001	<.0001	<.0001	0.454	0.012	0.910
	299	301	301	301	301	301	308	308	308	308	308	256	308	154
rtvwi	-0.098	0.361	0.391	0.335	-0.213	0.301	0.975	0.869	1.000	-0.796	0.969	0.023	0.108	-0.039
	0.089	<.0001	<.0001	<.0001	0.000	<.0001	<.0001	<.0001		<.0001	<.0001	0.709	0.059	0.631
	299	301	301	301	301	301	308	308	308	308	308	256	308	154
recivwi	0.162	-0.240	-0.255	-0.223	0.132	-0.200	-0.655	-0.453	-0.796	1.000	-0.916	-0.167	-0.091	0.012
	0.005	<.0001	<.0001	<.0001	0.022	0.001	<.0001	<.0001	<.0001		<.0001	0.008	0.111	0.881
	299	301	301	301	301	301	308	308	308	308	308	256	308	154
logvwi	-0.123	0.331	0.357	0.307	-0.189	0.275	0.891	0.731	0.969	-0.916	1.000	0.077	0.096	-0.039
	0.033	<.0001	<.0001	<.0001	0.001	<.0001	<.0001	<.0001	<.0001	<.0001		0.218	0.093	0.633
	299	301	301	301	301	301	308	308	308	308	308	256	308	154
DecCls	-0.441	-0.147	-0.071	-0.191	0.312	-0.236	-0.017	-0.047	0.023	-0.167	0.077	1.000	0.560	-0.069
	<.0001	0.019	0.259	0.002	<.0001	0.000	0.790	0.454	0.709	0.008	0.218		<.0001	0.480
	254	256	256	256	256	256	256	256	256	256	256	256	256	106
YSH	-0.397	-0.141	-0.095	-0.166	0.225	-0.190	0.122	0.143	0.108	-0.091	0.096	0.560	1.000	-0.068
	<.0001	0.014	0.098	0.004	<.0001	0.001	0.033	0.012	0.059	0.111	0.093	<.0001		0.402
	299	301	301	301	301	301	308	308	308	308	308	256	308	154
Orientation	0.258	0.157	0.144	0.160	-0.140	0.158	-0.032	-0.009	-0.039	0.012	-0.039	-0.069	-0.068	1.000
	0.002	0.058	0.081	0.053	0.091	0.055	0.691	0.910	0.631	0.881	0.633	0.480	0.402	
	147	147	147	147	147	147	154	154	154	154	154	106	154	154

Where HAS is height above stream
DMC is diameter at mid creek and sqdmc, rtdms, recidmc, logdmc are various transformations of DMC.
VWI is valley width index and sqvwi, rtvwi, recivwi, logvwi are various transformations of VWI.
Deccls is Decay class of log ranging from 1-4.
YSH is years since harvest which is 0-5yrs, 6-10yrs, 11-15yrs and 16-20yrs.

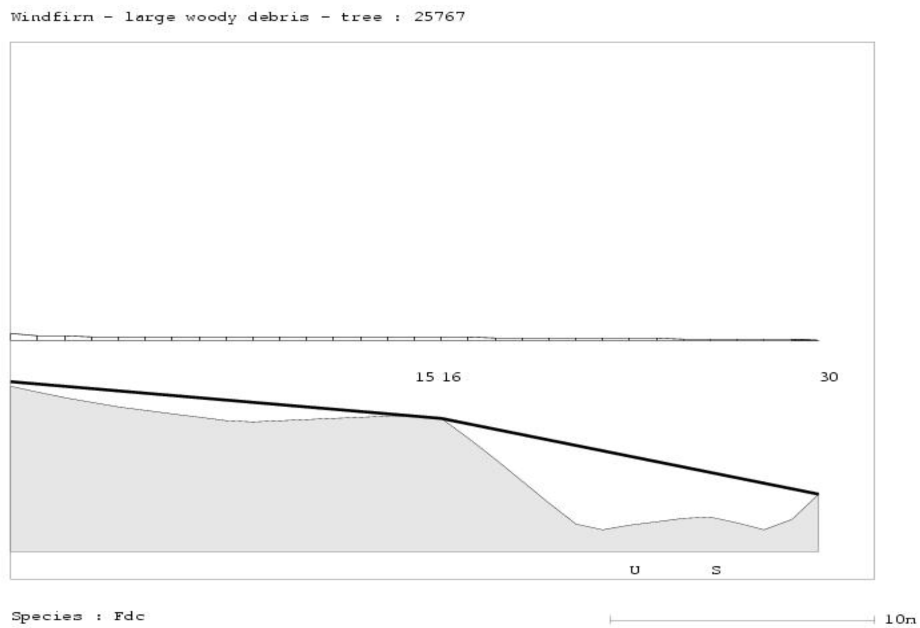
Appendix 9- Pearson's correlations for variables (Bamfield)

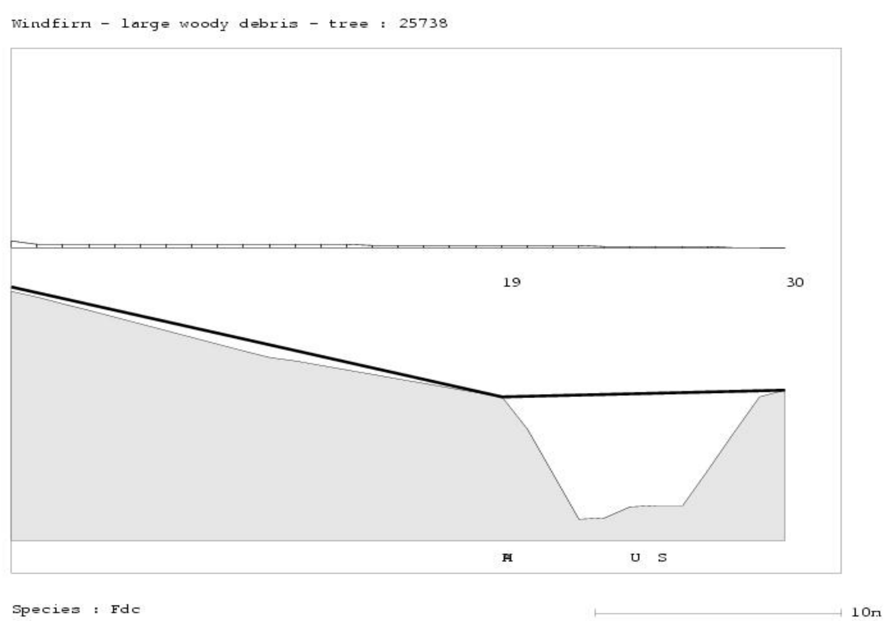
	HAS	DMC	sqdmc	rtdmc	recidmc	logdmc	VWI	sqvwi	rtvwi	recivwi	logvwi	DecCls	YSH	Orientation
HAS	1.000	0.099	0.106	0.088	-0.055	0.076	0.085	0.085	0.078	-0.046	0.068	-0.503	-0.325	0.057
		0.064	0.048	0.099	0.306	0.154	0.110	0.114	0.143	0.393	0.202	<.0001	<.0001	0.290
	352	352	352	352	352	352	352	352	352	352	352	351	352	352
DMC	0.099	1.000	0.879	0.968	-0.720	0.894	-0.036	-0.046	-0.032	0.026	-0.029	0.008	-0.043	0.126
	0.064		<.0001	<.0001	<.0001	<.0001	0.505	0.385	0.553	0.628	0.588	0.883	0.417	0.018
	352	352	352	352	352	352	352	352	352	352	352	351	352	352
sqdmc	0.106	0.879	1.000	0.740	-0.398	0.601	-0.029	-0.033	-0.026	0.019	-0.024	-0.031	-0.048	0.090
	0.048	<.0001		<.0001	<.0001	<.0001	0.593	0.539	0.625	0.717	0.657	0.557	0.368	0.091
	352	352	352	352	352	352	352	352	352	352	352	351	352	352
rtdmc	0.088	0.968	0.740	1.000	-0.855	0.977	-0.045	-0.058	-0.041	0.037	-0.039	0.028	-0.039	0.125
	0.099	<.0001	<.0001		<.0001	<.0001	0.398	0.282	0.442	0.493	0.469	0.602	0.470	0.019
	352	352	352	352	352	352	352	352	352	352	352	351	352	352
recidmc	-0.055	-0.720	-0.398	-0.855	1.000	-0.942	0.078	0.087	0.075	-0.074	0.074	-0.051	0.014	-0.077
	0.306	<.0001	<.0001	<.0001		<.0001	0.146	0.103	0.159	0.167	0.165	0.339	0.788	0.150
	352	352	352	352	352	352	352	352	352	352	352	351	352	352
logdmc	0.076	0.894	0.601	0.977	-0.942	1.000	-0.057	-0.069	-0.053	0.050	-0.051	0.042	-0.032	0.112
	0.154	<.0001	<.0001	<.0001	<.0001		0.289	0.195	0.321	0.351	0.340	0.437	0.544	0.035
	352	352	352	352	352	352	352	352	352	352	352	351	352	352
VWI	0.085	-0.036	-0.029	-0.045	0.078	-0.057	1.000	0.950	0.989	-0.871	0.961	-0.217	-0.292	0.071
	0.110	0.505	0.593	0.398	0.146	0.289		<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.186
	352	352	352	352	352	352	352	352	352	352	352	351	352	352

sqvwi	0.085	-0.046	-0.033	-0.058	0.087	-0.069	0.950	1.000	0.897	-0.703	0.835	-0.160	-0.222	0.050
	0.114	0.385	0.539	0.282	0.103	0.195	<.0001		<.0001	<.0001	<.0001	0.003	<.0001	0.350
	352	352	352	352	352	352	352	352	352	352	352	351	352	352
rtvwi	0.078	-0.032	-0.026	-0.041	0.075	-0.053	0.989	0.897	1.000	-0.930	0.991	-0.232	-0.306	0.078
	0.143	0.553	0.625	0.442	0.159	0.321	<.0001	<.0001		<.0001	<.0001	<.0001	<.0001	0.144
	352	352	352	352	352	352	352	352	352	352	352	351	352	352
recivwi	-0.046	0.026	0.019	0.037	-0.074	0.050	-0.871	-0.703	-0.930	1.000	-0.970	0.225	0.274	-0.086
	0.393	0.628	0.717	0.493	0.167	0.351	<.0001	<.0001	<.0001		<.0001	<.0001	<.0001	0.108
	352	352	352	352	352	352	352	352	352	352	352	351	352	352
logvwi	0.068	-0.029	-0.024	-0.039	0.074	-0.051	0.961	0.835	0.991	-0.970	1.000	-0.238	-0.306	0.083
	0.202	0.588	0.657	0.469	0.165	0.340	<.0001	<.0001	<.0001	<.0001		<.0001	<.0001	0.120
	352	352	352	352	352	352	352	352	352	352	352	351	352	352
DecCls	-0.503	0.008	-0.031	0.028	-0.051	0.042	-0.217	-0.160	-0.232	0.225	-0.238	1.000	0.460	-0.013
	<.0001	0.883	0.557	0.602	0.339	0.437	<.0001	0.003	<.0001	<.0001	<.0001		<.0001	0.807
	351	351	351	351	351	351	351	351	351	351	351	351	351	351
YSH	-0.325	-0.043	-0.048	-0.039	0.014	-0.032	-0.292	-0.222	-0.306	0.274	-0.306	0.460	1.000	-0.054
	<.0001	0.417	0.368	0.470	0.788	0.544	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001		0.313
	352	352	352	352	352	352	352	352	352	352	352	351	352	352
Orientation	0.057	0.126	0.090	0.125	-0.077	0.112	0.071	0.050	0.078	-0.086	0.083	-0.013	-0.054	1.000
	0.290	0.018	0.091	0.019	0.150	0.035	0.186	0.350	0.144	0.108	0.120	0.807	0.313	
	352	352	352	352	352	352	352	352	352	352	352	351	352	352

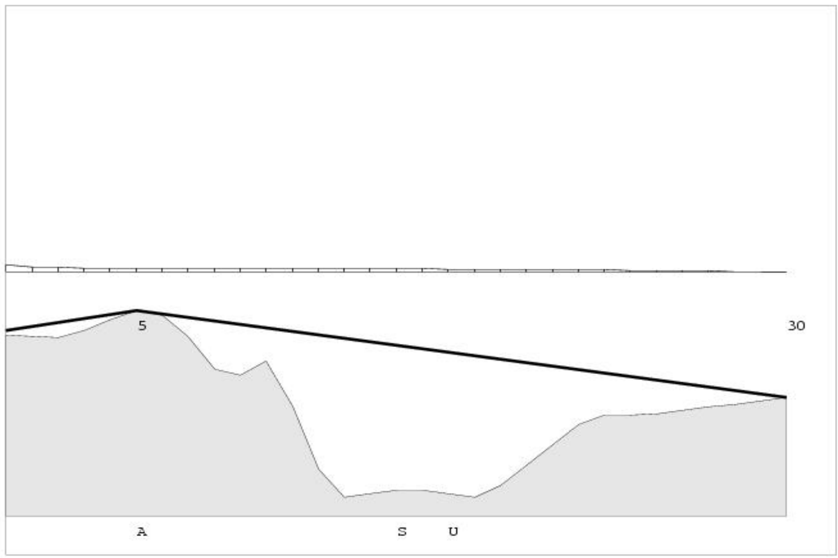
Where HAS is height above stream
DMC is diameter at mid creek and sqdmc, rtdms, recidmc, logdmc are various transformations of DMC.
VWI is valley width index and sqvwi, rtvwi, recivwi, logvwi are various transformations of VWI.
Deccls is Decay class of log ranging from 1-4. YSH is years since harvest which is 0-5yrs, 6-10yrs, 11-15yrs and 16-20yr

Appendix 10- LWDSPAN module, tree profile images (from Tim Shannon)



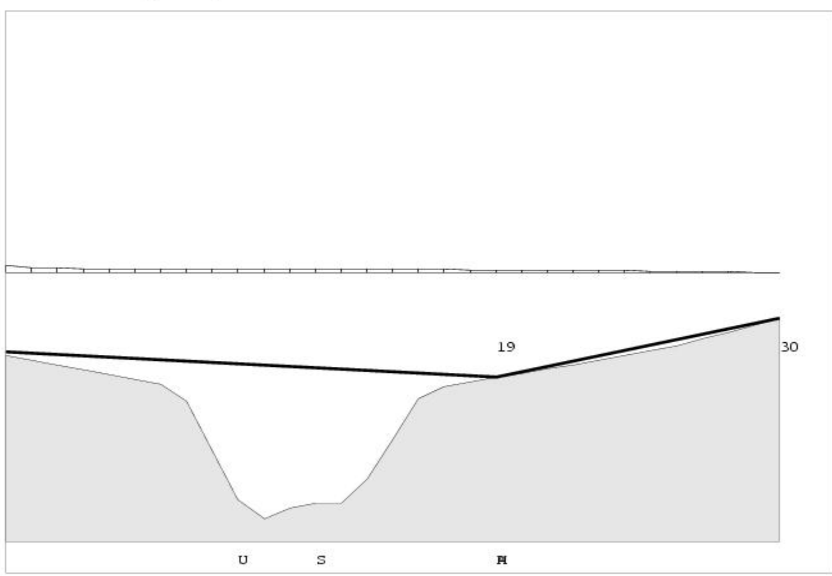


Windfirm - large woody debris - tree : 24724



Species : Fdc   10m

Windfirm - large woody debris - tree : 24651



Species : Fdc   10m