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Windthrow and recruitment of large woody debris in riparian stands

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ABSTRACT

To document the impacts of windthrow in riparian leave strips and identify the components needed for small stream large woody debris (LWD) recruitment modeling, we monitored nine small streams at a temperate rainforest site in coastal British Columbia. This study was a component of a larger integrated study of forest management impacts on small streams. A series of small clearcuts were harvested in 1998 in a 70-year-old second growth stand that had regenerated naturally following logging and wildfire. Three cutblocks each were assigned to 10 m and 30 m buffer width treatments and three areas were assigned as unharvested controls. Seven years after the 1998 logging, all logs greater than 10 cm diameter that spanned at least part of stream channel width were measured. A total of 179 logs were recorded. Post-harvest windthrow was higher in the 10 m buffer treatment, while competition-related standing tree mortality was higher in the controls. The major windthrow events had occurred in the first and second years after logging of adjacent stands. There was no significant difference in the number of spanning and in-stream logs in the 10 m, 30 m buffer and control treatments. More than 90% of the LWD was in the 10–30 cm diameter classes. The majority of logs were oriented perpendicular to the stream channel. At the time of measurement, the majority of these trees were still suspended above the stream channel, indicating that the recruitment of logs into the stream channel is a long-term process. Time to recruitment into the channel is dependent on log and valley geometry, log size, species, and log condition prior to toppling. Log height above stream was negatively correlated with log decay class and valley width. Log length was negatively correlated with state of decay, and many windthrown logs were in an advanced state of decay before they entered the stream.

1. Introduction

Changes in forest practice 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 policies require retention of treed buffer strips along relatively small stream channels if they have fish populations (Wang et al., 2002). These unharvested strips are intended to minimize impacts of forest management activities on water quality, aquatic ecosystems and riparian community diversity (BCMOF, 1995). In-stream large woody debris (LWD) helps to structure fish habitat (Bisson et al., 1987), shape channels (Swanson et al., 1976), and trap sediments (Swanson and Lienkaemper, 1978; Gurnell et al., 2005). Larger wood pieces tend to remain where they are delivered in small streams, providing long-term benefits (Gurnell et al., 2002). The transfer of LWD from streamside forests to the stream and river systems creates a strong linkage between terrestrial and aquatic ecosystems (Lienkaemper and Swanson, 1987). The process of transfer of LWD from forests to streams is complex, and occurs in phases, starting with tree fall.

In riparian buffer strips, post-harvest windthrow is a major source of tree falls. Approximately 15% of cutblock boundary segments in wind exposed areas of coastal BC are partially windthrown following harvesting (Lanquaye-Opoku and Mitchell, 2005; Scott and Mitchell, 2005), and riparian buffers are particularly susceptible (e.g. Steinblums et al., 1984; Rollerson and McGourlick, 2001). To design effective riparian prescriptions, we need to understand the ecological impacts of windthrow in both the short and longer term. Potential 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).

There are a number of models that aim to characterize the input, storage and loss of LWD in stream systems (e.g. STREAMWOOD, Meleason, 2001; RAIS, Welty et al., 2002; AQUAWOOD, Wei, 2005b). In these models, tree fall rates are usually tied to standing tree mortality rates. Tree fall direction is either treated as random or is conditioned by the user based on expert knowledge or empirically derived data. If it is explicitly dealt with at all, windthrow in newly exposed riparian buffers is often viewed as a pulse source of LWD input (e.g. RAIS, Welty et al., 2002). Given the geometry of

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Table 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 $\geq 60^{\circ}$)
	MV	Moderate V-shaped valley (side slope $>30^{\circ}$, $<60^{\circ}$)
	OV	Open V-shaped valley (side slope $\leq 30^{\circ}$)
Broad valley type	CT	Constraining terraces. Terraces high and close to active channel
	MT	Multiple terraces. Surface with varying height and distance from the channel
	WF	Wide active flood plain. Significant portion of valley floor influenced by annual floods
Bankfull channel width	BCW	Distance across channel at bankfull flow
Valley floor width	VFW	Distance of valley across channel
Valley floor index	VFI	It is a ratio of VFW to BCW
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 redcedar; Fd: Douglas-fir; Ss: sitka spruce; Ep: Paper birch; Dr: red alder; Mb: Maple
Decay class	Deccls	Classification system for logs based on decay (Table 2) (Bartels 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
Diameter at mid-stream	DMC	Diameter of log measured at middle of stream
Bankfull channel width length	BCWL	The portion of log in active channel measured with tape
Total length	TL	The total length of log
Debris type		RN: rootwad attached to ends; N: broken ends; C: cut ends
Base diameter	Base_dia	Diameter at base of the downed logs
Length mid-stream	Len_midcreek	Distance of log from mid-stream 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 stream

small stream valleys, it is more likely that downed trees, whether from standing tree mortality or from pulses of windthrow will be suspended above small streams rather than immediately entering the channel. The process by which these spanning logs enter the channel, and log condition at the time of channel entry is not well understood or modeled. The objectives of this research project were to:

(1) Evaluate the effect of riparian buffer width on windthrow and LWD recruitment and contrast this with unharvested controls.
(2) Investigate the condition of LWD.
(3) Document the geometry of post-harvest windthrow in riparian buffers of different widths.
(4) Develop the framework for a process model that simulates the supply of LWD of windthrow origin to streams within riparian buffers.

2. Methods

This study is a component of a larger integrated study of forest management impacts on small streams in second growth forests. The riparian areas investigated in this study are in dense young-mature conifer-dominated forests that have developed following harvest and wildfire. This is a common forest type in the low elevation areas of the north west coast of North America and small, fish bearing streams are abundant in these forests. The small streams riparian buffers experiment is located in the foothills of the Coast Mountains, approximately 60 km east of Vancouver, British Columbia (Feller and Sanders, 1999; Moore and Richardson, 2003). The climate is maritime and characterized by dry, warm summers and wet, cool winters. Total precipitation ranges between 2200 mm and 3000 mm per year. Snow falls only occasionally at these low elevations (120–450 m). Soils are shallow and are derived from glacial till and glacio-marine deposits. The topography varies from flat to hilly and gently rolling, with some bedrock knolls. The underlying geology of the study site is quartz diorite, diorite and granodiorite. The stands in the study area naturally regenerated following logging and wildfire in the 1930s and are dense and uniform in structure. The tree species include western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western redcedar (*Thuja plicata* Donn ex D. Don), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), paper birch (*Betula papyrifera* Marsh.), and red alder (*Alnus rubra* Bong.).

2.1. Experimental design

Two buffer width treatments (10 m and 30 m on each side of the stream), and unharvested controls were each replicated three times within the riparian buffers experiment. There were also three fully harvested blocks (0 m buffers), but these treatment units were not included in the LWD study since they had no post-harvest LWD recruitment. Harvesting commenced in the fall of 1998. Overstory vegetation plots were measured annually. These vegetation

Table 2
Classification of LWD decay classes (from 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

plots were 15 m long and 4 m wide, ran lengthwise parallel to the stream, and were repeated at 2 m and 15 m from the stream bank on each side of the stream. These 4 strip-plot clusters were replicated at two locations along the stream within each treatment unit. They represented vegetation dynamics for the buffers experiment (Miquelajauregui, 2008) and provided tree mortality data for this LWD study. Within each strip plot, the species, diameter at 1.3 m (DBH), height and status (standing live, standing dead, uprooted) in each year were recorded for each tree, starting the year prior to harvesting.

Transects were established up the centre of each stream within each treatment unit in the summer of 2006 using the protocol of Moore et al. (2002) as a basis for sampling and measurements. Since each treatment unit was at least 150 m long, we chose a transect length of 150 m. The streams were all under 5 m wide, and were incised, relatively straight, and constrained primarily by hill slopes and narrow fluvial terraces. To characterize stream conditions, each stream was divided into reaches whenever there was a major change in orientation of the stream, or in the channel or valley form. The bankfull channel width (BCW) and valley floor width (VFW) were measured in two locations within each reach (see Table 1 for a description of terms). The bankfull channel is the channel cross-section that would be flooded each year during peak flow. This is indicated by the absence of established perennial understory vegetation. The bearing, gradient and slope angle along the reach were recorded, as was the slope angle of the valley sides. The ratio of VFW to BCW gave valley floor index (VFI); this value indicates the degree to which the channel is constrained by fluvial terraces. The spanning logs in each transect were tagged with uniquely numbered plastic tree tags, usually near the mid-stream on the downstream side.

For downed trees to be tagged and measured they needed to be: fallen or windthrown since 1998, having at least a portion of the log length within (or above) the bankfull channel, greater than 10 cm in diameter at the mid-stream, and in decay class 1–3. We used the five class decay classification system which is extensively used in the U.S Pacific Northwest (Table 2). In this system, wood soundness or structural integrity is an explicit part of the classification and recently downed trees with intact fine branches and bark constitute the first decay class. Pre- versus post-harvest downed trees, were differentiated by the accumulation of litter, age of regeneration and state of revegetation on the exposed pit, rootwad and downed bole, using the condition of trees within the vegetation plots that were known to have windthrown immediately post-harvest as the benchmark.

Tagged, downed 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 point of commencement (POC) was recorded. The orientation of the tree top, DBH, length within the bankfull channel width, and total length of each downed tree were also recorded. To distinguish between the characteristics of downed material and the tree from which it was derived, we hereafter refer to downed tree boles as ‘logs’. Each log retained the number of the tree from which it was derived. If the tree bole was broken into multiple pieces within the bankfull channel width, those logs received the additional notation ‘a’, ‘b’ and so on. For each log, the base diameter, diameter at mid-stream (DMC), top diameter, log length, height above stream (HAS), log angle, span length and length mid-stream were recorded. Logs were classified according to log end conditions (e.g. rootwad still attached, cut ends, broken ends). Where logs were elevated above the bankfull height of the stream channel (e.g. height above stream > 0 cm), they are referred to as ‘spanning’ logs.

The experimental design is a replicated design with one factor, ‘treatment’ (with three levels: unharvested control, 10 m buffer, and 30 m buffer). The General Linear Model procedure (GLM, SAS Institute Inc., Cary, NC) was used to determine whether the diameter at mid-stream, number of logs by decay class (1, 2, and 3), in-stream, or spanning logs varied significantly among buffer treatments. 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. Observations from all treatments were pooled for the analysis of log geometry. Pearson correlation coefficients were used for assessing the correlations between height above stream and potential predictor variables such as log diameter, valley width and decay class. Multiple linear regression was then used to assess the combined utility of these variables in predicting LWD height above the stream. Variables with non-normal distributions were transformed prior to analysis.

3. Results

At the stand level, species composition was 51% western hemlock, 38% western redcedar, 6% Douglas-fir and 5% other species, primarily birch and alder. There was very little windthrow or recently downed material in these second growth stands prior to harvesting. Windthrow in the overstory vegetation plots was greatest in the first 1–2 winters following harvest of adjacent timber, however some windthrow occurred in subsequent years. After harvest in 1998, 11% of initially standing trees were blown down in the first and second years in the 10 m buffer treatment compared to 4% in the 30 m buffer and less than 1% in unharvested controls. There was minimal new windthrow in subsequent years until 2006

Table 3
General model for ANOVA design.

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

t is treatment (10 m buffer, 30 m buffer and unharvested control); r is the number of replications.

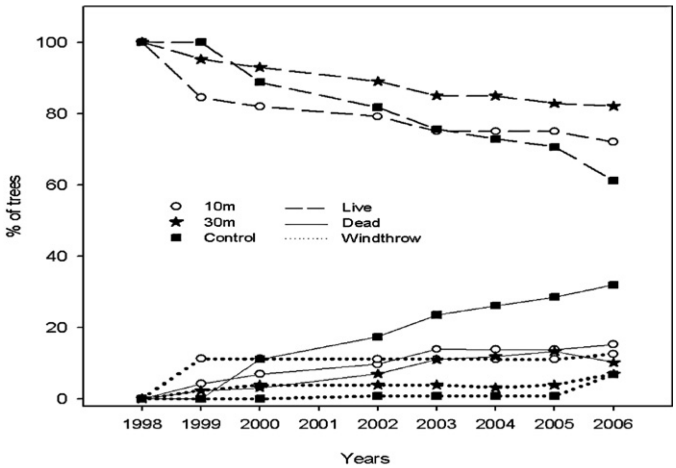

Fig. 1. The percentage of live, dead and windthrown trees in each of the three treatments for 8 years following harvest.

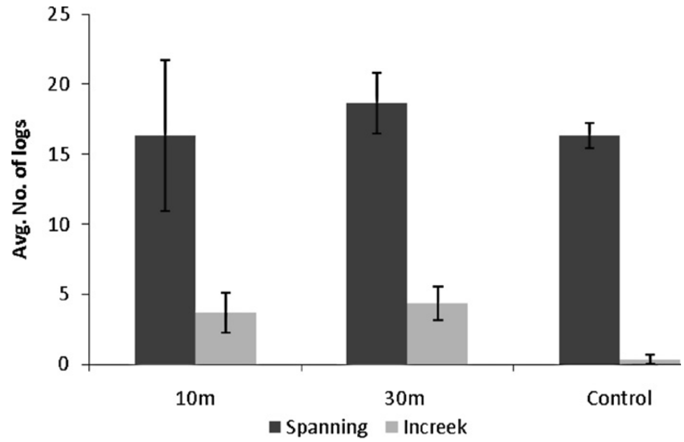

Fig. 2. Average number of spanning and in-stream logs (height above stream = 0) >10 cm diameter at mid-stream by treatment, all species, all decay class with SE bars.

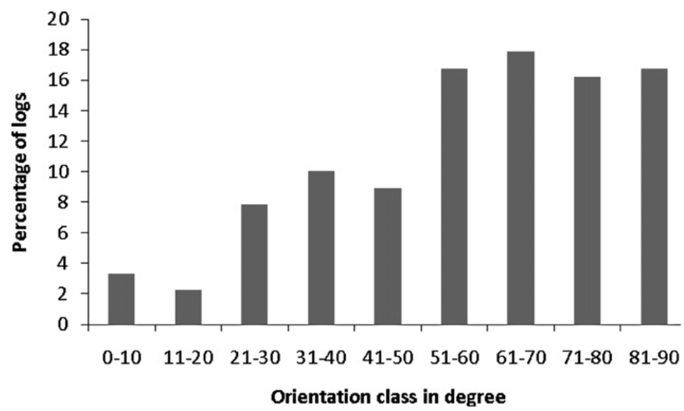

Fig. 3. Percentage of logs by orientation class in degrees where 0° is parallel to stream and 90° is perpendicular to stream, all treatments (n = 179).

when winter storms brought down some additional trees in both the buffer and control treatments (Fig. 1). Interestingly, in these dense second growth stands, there was still a significant amount of annual mortality in standing trees, particularly in the unharvested control, amounting to 30% of initially live trees in the control and 15% each in the 10 m and 30 m buffers after 8 years. The average diameter (DBH) of live, dead and windthrown trees were 35 cm, 13 cm, and 26 cm respectively for all treatments pooled.

A total of 179 logs (spanning and in-stream) were recorded in the stream transects (Table 4). Even after 8 years following harvesting and the post-harvest pulse of windthrow, 78% and 81% of logs in the 10 m and 30 m buffer treatments, respectively, were still elevated above the stream. In the unharvested control, 98% of downed logs were elevated above the stream. The average number of spanning logs was consistent among the treatments (16, 19 and 16 logs per 150 m of stream, for 10 m, 30 m and unharvested control respectively; Fig. 2). Few logs had dropped into the stream channel in any of the treatments (4, 4 and <1 logs per 150 m of stream for 10 m, 30 m, and unharvested control respectively). The dominant fall direction of windthrown trees was toward the west-northwest, while streams typically ran from north-south. Accordingly, most logs were oriented diagonal-perpendicular relative to the stream channel, with just 3% of logs falling parallel to the stream (Fig. 3).

Of the log variables analyzed, only the number of logs in decay class 3 was significantly different between buffer treatments (p = 0.015) (Table 5). There were no significant differences in the average number of decayed logs in decay classes 1 and 2 (p = 0.30) between buffer widths, however there were 3 times as many logs in decay class 3 in the 30 m buffer than in the 10 m and control treat-

Table 5
Analysis of variance results. Bold letters indicate significant results for α = 0.05.

Variables	p-Value
Number, all logs	0.39
Number of spanning logs	0.85
decay class 1	0.40
decay class 2	0.80
decay class 3	**0.015**
Number of in-stream logs	0.51
decay class 1	–
decay class 2	0.30
decay class 3	0.87
DMC	0.94

Table 4
Stream characteristics and abundance and dimensions of post-harvest spanning and in-stream large woody debris (LWD) in the sample streams.

Stream	Watershed area (ha)	No. of reaches	BCW (m)	VFW (m)	LWD/150 m	DBH (cm)	DMC (cm)	Log length (m)	BCWL (m)	HAS (cm)
C (10 m)	89.1	11	2.94 (0.21)	11.03 (2.34)	28	24.92 (1.92)	19.48 (1.41)	24.71 (1.77)	3.51 (0.31)	141.4 (13.5)
F (10 m)	11.5	12	1.96 (0.22)	7.10 (1.21)	18	20.86 (3.18)	14.49 (1.19)	15.39 (1.86)	2.07 (0.37)	45.6 (11.9)
G (10 m)	83.5	11	3.43 (0.15)	7.57 (0.26)	14	25.09 (3.44)	17.79 (1.68)	20.26 (1.48)	2.44 (0.19)	51.6 (12.1)
D (30 m)	43.3	13	1.60 (0.20)	9.99 (1.43)	29	24.68 (2.46)	17.31 (1.35)	18.11 (2.08)	3.04 (0.25)	65.3 (13.9)
H (30 m)	55.4	9	3.79 (0.25)	23.82 (2.46)	19	28.72 (2.76)	19.23 (1.78)	16.99 (1.67)	4.40 (0.43)	61.6 (12.1)
Sk (30 m)	18.6	10	2.73 (0.24)	9.01 (1.01)	21	23.36 (2.62)	13.85 (0.76)	19.62 (2.51)	2.65 (0.24)	51.9 (11.2)
MC control	29.7	9	4.46 (0.45)	10.77 (0.74)	17	25.49 (3.39)	26.84 (3.39)	15.6 (1.76)	6.54 (0.91)	90.9 (14.4)
EC control	44.0	7	3.26 (0.33)	7.18 (0.65)	18	13.982 (0.5)	11.83 (0.31)	13.87 (0.93)	1.05 (0.17)	109.7 (17)
SC control	111.0	5	4.23 (1.12)	6.56 (1.67)	15	18.87 (1.02)	15.81 (0.94)	18.31 (1.5)	4.96 (0.39)	139.5 (15.6)
Mean (SE)	54.01 (11.3)	9.66 (0.83)	3.15 (0.32)	10.34 (1.77)	19.89 (1.7)	22.89 (2.37)	17.41 (1.42)	18.1 (1.72)	3.41 (0.36)	84.17 (13.52)

Means are followed by standard errors in parentheses.

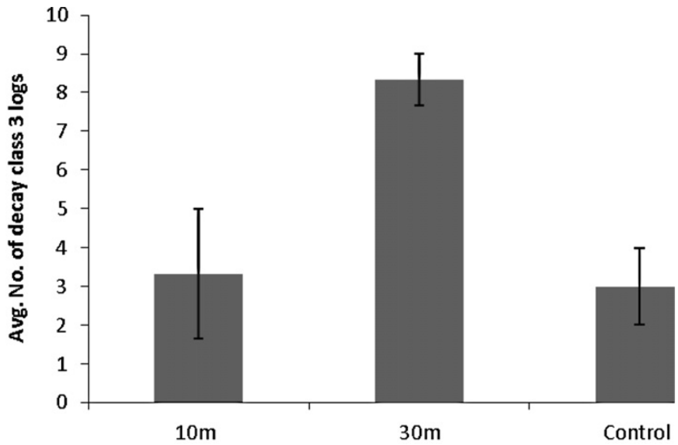

Fig. 4. Average number of logs in all size classes for decay class 3 logs, by treatment.

ments (Fig. 4). The proportion of logs in advanced stages of decay was higher for in-stream logs than for spanning logs (Fig. 5).

The mean log diameter at mid-stream (DMC) was 17 cm, with no difference between treatments ($p = 0.94$, $n = 179$). Debris with the rootwad attached to the bole was more abundant (71%) than debris with broken (28%) or cut ends (1%). As was the case for the standing timber, western hemlock was the dominant species in the stream channel, followed by western redcedar. The majority (77%) of the logs were in the 10–20 cm DMC class with only 2% larger than 40 cm DMC (Fig. 6). Since the diameter distribution of standing live trees was near normal around a mean diameter of 30 cm, the LWD

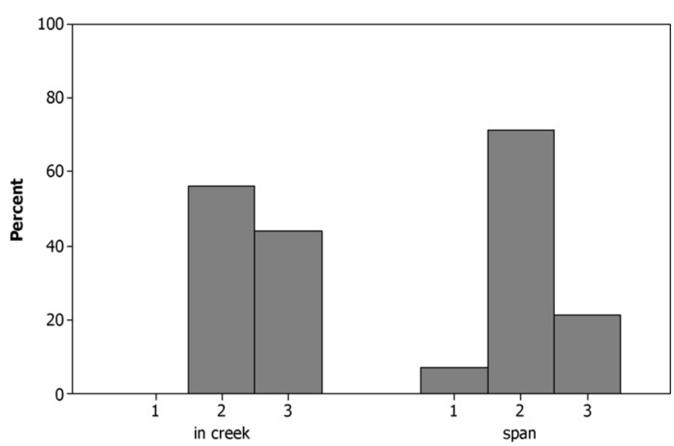

Fig. 5. Percent of spanning and in-stream logs by decay classes, all size classes and decay classes (log decay classes from Bartels et al., 1985; MOFR, 2007).

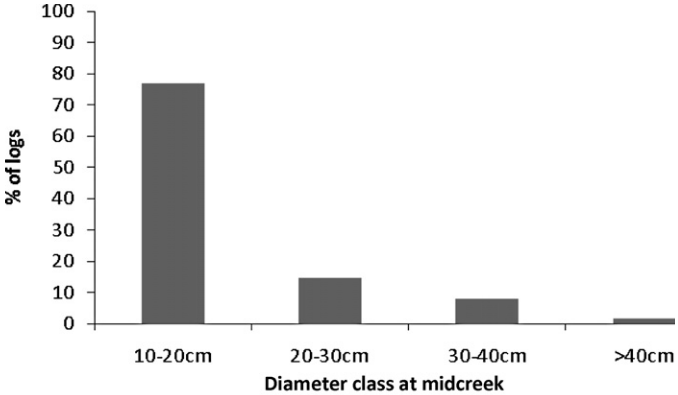

Fig. 6. Percentage of logs (in-stream and spanning logs) by diameter at mid-creek.

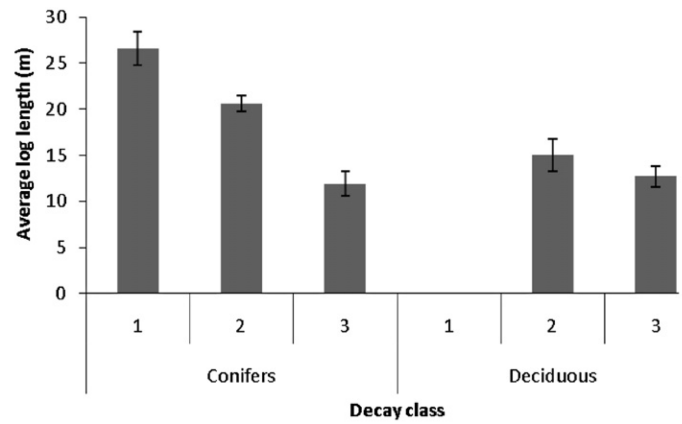

Fig. 7. Average log length (m) by decay class and species. Conifers include western hemlock, western redcedar, sitka spruce, and Douglas-fir. Deciduous include paper birch, red alder, big leaf maple, and black cottonwood. For all in-stream and spanning logs, all size classes.

was smaller on average than the standing trees. Approximately, 10% of uprooted western redcedar were still alive and spanning the stream, whereas all of the uprooted western hemlock trees were dead. 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. 7).

The variables most strongly correlated with log height above stream were decay class ($r = -0.35$, $p < 0.0001$), reciprocal of valley width index ($r = 0.31$, $p < 0.0001$) and logarithm of diameter at mid-stream ($r = 0.26$, $p = 0.0005$). Accordingly, multiple linear regressions were fitted for predicting height above stream using these variables. Though the intercept and all the variables DMC, RECIVWI and Deccls were significant ($\alpha = 0.05$), the R^2 value for the best regression was low (0.21; Table 6). The average length of the logs decreased as decay class increased, for both conifer and deciduous logs. Furthermore, within decay class 2, deciduous logs were shorter than conifer logs (Fig. 7).

4. Discussion

A key reason for retaining buffers adjacent to streams is to ensure a sustained supply of LWD to the aquatic ecosystem (e.g. Van Sickle and Gregory, 1990). The numbers of trees available as source of LWD depends on stand density, width of the treed zone, valley geometry and fall directionality. The tree-fall rate will depend on the severity and timing of post-harvest windthrow events, and standing tree mortality, and how these vary with buffer condition. Grizzel and Wolff (1998) suggested that in a managed forest landscape with small, low gradient streams, windthrow in riparian buffers is likely the most significant mechanism by which LWD is recruited into stream channels. They found higher total tree fall rates in narrower buffers and a 34% increase in within-channel

Table 6
Multiple linear regression for predicting height above stream (HAS, cm) using diameter at mid-stream (DMC, cm), reciprocal of valley width index (RECIVWI) and decay class (Deccls).

Variables	Parameter estimates	Standard error	*p*-Value	R^2	Root MSE	*n*
Intercept	106.55	29.4	0.0004			
DMC	1.30	0.63	0.0407			
RECIVWI	106.80	27.13	0.0001			
Deccls	−38.69	9.90	0.0001			
MODEL				0.2142	64.72	165

HAS, height above stream; DMC, diameter at mid-stream; VWI, valley width index; Deccls, decay class of log. Level of significance, $\alpha = 0.05$.

LWD pieces in small coastal streams in Washington State. In our riparian buffers experiment, we found higher windthrow rates in the 10 m and 30 m buffers than in the control, but a higher rate of standing tree mortality due to ongoing competitive exclusion in the controls. In consequence, there was no difference in the total number of spanning or in-stream logs or the size of these logs between buffers and controls in our study. While windthrow is important, mortality due to competitive exclusion is a significant source of spanning LWD in all treatments. The number of spanning LWD pieces per linear meter of stream channel in our study is lower than reported in other studies in comparable forests, likely because we were recording only post-harvest LWD. In contrast to our value of 0.13 LWD/linear meter, Long (1987) found 0.45 LWD/linear meter of stream in an Oregon coastal stream in a 50+ year-old stand. Heimann (1988) found 0.61 LWD/linear meter of stream in an 80–140 year-old stand in coastal Oregon, and Ralph et al. (1994) found 0.25 LWD/linear meter of stream in an 80+ year-old stand in Western Washington.

When adjacent timber is harvested, the width of the unharvested buffer affects 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 buffered sections was derived from within 30 m of the channel, whereas in the unlogged stand 96% of LWD recruits were derived from within 20 m. However, they found that the majority of LWD was coming from within 10 m of the channel for buffer and unlogged stands respectively. McDade et al. (1990) examined LWD sources in first to third order streams in coastal Washington and Oregon and found that 70% of LWD pieces came from trees rooted within 20 m of the stream channel. In our study at MKRF, the similarity in number of spanning and in-stream logs between the 30 m buffer and 10 m buffers, and unharvested control suggests that 10 m buffers are adequate for maintaining the supply of LWD in the short term.

We found that small diameter trees contributed disproportionately to LWD recruitment. Similar results have been reported in other LWD studies in coastal and continental forests (e.g. Hauer et al., 1999; Berg et al., 1998; Richmond and Fausch, 1995). The preferential recruitment of small LWD is in part due to the ongoing competition mortality which is a normal phenomenon in high density young-mature stands (e.g. Oliver and Larson, 1990). Windthrow has the potential to introduce larger trees (e.g. Scott and Mitchell, 2005), but in our case, the absolute difference in windthrow levels between buffers and controls was relatively small and did not result in an overall increase in LWD dimensions in the buffer treatments. The increased light levels and wind-induced thinning in the buffers may accelerate the development of larger diameter trees in these treatments. Furthermore, these buffer stands will be more exposed than controls to the effects of periodic severe storms for many years. Longer term studies will be necessary to characterize differences in wood recruitment dynamics between buffers and controls.

Windthrow in cutblock edges and buffers is typically greatest in the first 1–2 post-harvest winter seasons (Rollerson and McGourlick, 2001). We found a similar pulse of post-harvest windthrow in the MKRF buffers experiment. However, this pulse of windthrow does not immediately result in LWD within the stream channel. We found that even 8 years after harvest, 80% of windthrown logs were still spanning the stream in the 10 m and 30 m buffers. Grizzel and Wolff (1998) reported that 75% of post-harvest windthrow LWD was suspended in their study of coastal streams. Wei (2005a) and Chen et al. (2006) also found the majority of LWD was located above the bankfull height in small sized streams in the continental forests of the BC Interior. These results have important implications for debris recruitment modeling. The first is that the connection between the level of post-harvest windthrow in buffers, and the ultimate effect of this windthrow on stream channel properties is very indirect. Actual recruitment of windthrown material into the stream may take place over decades following a short-term pulse of post-harvest windthrow. Secondly, most windthrown logs enter the stream channel only after decay and subsequent breakage. This slow recruitment following a pulse of mortality appears to be similar to the process following wildfires (e.g. Powell, 2006; Jones and Daniels, 2008), however there are likely important differences in decay processes between live trees that are uprooted by wind and standing fire-killed trees.

The relationship between decay and log breakage is interesting and important for LWD recruitment modeling and understanding the subsequent role and persistence of in-stream LWD. If logs decayed uniformly from the outside-in along their entire length, one would expect that decaying logs would fail near mid suspension. However, we observed that logs decayed more rapidly from the upper broken end where they were in contact with the soil, breaking into relatively short chunks from the upper end. This manner of decay is important. If the majority of spanning material eventually enters the stream channel as short, well-decayed logs, these logs may not provide the long-term in-stream role in channel structuring suggested by Gurnell et al. (2002). Further study of the condition, residency time and role of LWD material that enters streams by this route is warranted.

The orienting effects of wind damage are also important for LWD recruitment modeling. With a sampling rule that trees must cross at least part of the stream channel in order to be tallied, it is not surprising that few downed trees that run parallel to the stream are sampled. The area for potential recruitment is much larger for trees falling perpendicular to stream direction. However, our vegetation plot results showed that windthrow was strongly oriented perpendicular to the riparian buffers. This windthrow orientation is logical given that wind exposure and wind loading is higher where wind comes from directions perpendicular to the buffer, and was also observed by Rollerson and McGourlick (2001) in their studies on Vancouver Island. Regardless of the initial orientation of material that enters streams, stream energy can re-orient it (e.g. Chen et al., 2006), but this is not typically the case in small streams (e.g. Bilby and Ward, 1989; Richmond and Fausch, 1995). Our streams were all under 5 m wide and only 3% of in-stream logs were oriented parallel to the stream.

Grizzel and Wolff (1998) stated that the time between initial tree fall and the secondary phase when logs break apart and enter the channel depends upon species, size and condition of the wood piece. Our methodology in this study did not permit time to recruitment to be measured directly, but the trends in height above stream provide some insights into the governing processes and indicate how predictive models can be developed. The initial log height above stream depends on the interaction of log orientation and stream valley width. Smaller logs decayed more rapidly than larger ones. The logs failed primarily through decay at the upper end, progressively shortening and dropping closer to the water. Accordingly, the height above stream of suspended logs provides an indication of the progression towards in-stream recruitment. To model the time to in-stream LWD deposition, it is therefore necessary to characterize initial LWD position, valley geometry, and species-specific decay rates. It is also necessary to use faster decay rates where the log contacts the ground.

Windthrow as a source of LWD recruitment is ignored in recruitment models except for CWD (Bragg et al., 2000), in which users specify rate of windthrow as a fraction of live trees per year. Neither AQUAWOOD (Wei, 2005b), RAIS (Welty et al., 2002), STREAMWOOD (Meleason, 2001) nor CWD (Bragg et al., 2000) account for the initial position of uprooted trees relative to the stream. Nor do they have submodels that specifically account for the lag between tree fall and in-stream recruitment. In order to address this conceptual gap in LWD models, it is necessary to represent the valley

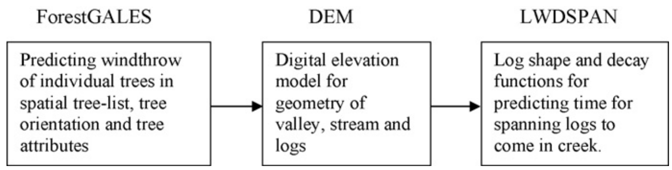

Fig. 8. Information flow between ForestGALES and LWDSPAN recruitment model for windthrow-derived large woody debris.

and stream channel geometry, the geometry and initial condition of spanning LWD, and to introduce a decay function for LWD change in condition over time. Appropriate functional forms for LWD decay functions are documented in the literature (Harmon et al., 1986), along with coefficients for common species. Decay rates vary with temperature and humidity (Mackensen et al., 2003) and riparian zones are typically more humid than upland forests, so decay rates should be locally estimated. To provide further realism in riparian buffers exposed by harvesting, the recruitment model can be driven by a windthrow prediction model such as ForestGALES (Gardiner et al., 2008). The variant of this model used in British Columbia is coupled with the stand growth and yield model TASS and produces a spatially explicit tree list. Since the tree list can be derived from plot data or growth models, it would also be possible to identify which trees will die and subsequently fail due to competition mortality. The LWDSPAN submodel 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. Resistive moments are adjusted annually based on decay and loss of effective diameter. To accurately portray log geometry, it is necessary to include a digital elevation model of terrain adjacent to the stream channel. The flow of information between ForestGALES and LWDSPAN is shown in Fig. 8.

5. Conclusion

In riparian buffers, recruitment of logs into stream channels where they can play a role in stream morphology lags behind the post-harvest pulse of windthrow by many years. This lag time depends on the size, species and initial condition of the logs, and their direction of fall relative to the geometry of the stream valley. These components can be characterized in submodels of LWD recruitment models. Logs that initially span the stream are in a state of advanced decay before they enter the stream channel. This has implications for their in-stream role and residence time and needs further investigation.

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