TFW Effectiveness Monitoring Report

STREAMSIDE BUFFERS AND LARGE WOODY DEBRIS RECRUITMENT: EVALUATING THE EFFECTIVENESS OF WATERSHED ANALYSIS PRESCRIPTIONS IN THE NORTH CASCADES REGION

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ABSTRACT
Forest management prescriptions implemented as part of Washington's Watershed Analysis process have resulted in the retention of streamside buffer strips that afford a greater degree of stream protection than earlier practices. A primary objective in establishing these buffers is to recruit large woody debris to create and maintain fish habitat. In this study, we evaluated the effectiveness of Watershed Analysis prescriptions in recruiting large woody debris by examining 10 streamside buffers in Washington's North Cascades. We evaluated effectiveness in three ways: 1) by comparing debris frequency to targets derived from Watershed Analysis resource condition indices (Washington Forest Practices Board 1997) and a channel-width dependent regression equation (Bilby and Ward 1989); 2) by comparing the size of debris recruited from buffers to targets based on channel-width dependent regression equations (Bilby and Ward 1989); and 3) by comparing debris recruitment between three buffer width classes. In addition, related to 2) above, we modeled forest stand growth to estimate time-to-recruitment of target-sized debris for sites currently below the target diameter.

Habitat quality at nine of 10 sites rated "good" based on the Watershed Analysis debris frequency targets while seven of 10 sites met the Bilby and Ward target for debris frequency. However, only four sites rated "good" based on "key" piece frequency targets for Watershed Analysis. This indicates that while most sites are meeting frequency targets, there is a disproportionate number of small debris pieces relative to larger, more stable pieces. The average diameter of debris recruited from buffers was below the Bilby and Ward target at all sites, however, the average length exceeded the target at all sites. An evaluation of average piece volume indicated that longer piece lengths did not compensate for deficits in piece diameters, as seven of 10 sites failed to meet the debris volume target. Growth modeling suggests that due to bole taper, only trees in close proximity to the stream will meet debris diameter targets within the next 25 years (stand age 75 years). Trees further from the stream will require one to two decades additional growth before meeting the diameter target (stand age 85 to 100 years).

Buffers in the 20-30 m and >30 m class contributed 19 and 28 percent of debris pieces, respectively outside 20 meters from the stream. This suggests a substantial portion of the total debris load is recruited from the outer margins of these wider buffers and narrower buffers limit debris recruitment. Buffer orientation with respect to the direction of damaging winds influenced the probability of debris recruitment. Trees in buffers oriented perpendicular to the direction of damaging winds (i.e., east-west) had a higher likelihood of being recruited relative to buffers oriented parallel to damaging winds (i.e., north-south). Post-harvest buffer mortality, primarily as a result of wind damage, ranged from 2.9 to 56.8 percent of stand basal area and 4.8 to 60.5 percent of stem density. Continued mortality in the form of wind damage is likely to reduce the capacity of these sites to recruit an adequate supply of target-sized debris in the future.

This study demonstrates that short-term post-harvest debris recruitment from streamside forest buffers is heavily influenced by windthrow. The quantity and quality of debris recruited will be a function of windthrow magnitude, buffer orientation, and stand characteristics. From a fish habitat perspective, accelerated rates of windthrow should be minimized to maintain stand density and allow for the continued growth and development of streamside buffer trees. Ideally, debris recruitment from the buffer would mimic the natural or background rate to ensure a continuous supply of debris over the long term. In order to achieve these objectives, natural resource managers must gain a better understanding of the factors influencing windthrow patterns at local and regional levels and implement management practices aimed at minimizing its occurrence.

INTRODUCTION

The ecological importance of large woody debris (LWD) in stream ecosystems of the Pacific Northwest has gained much attention in recent years. The influence of large woody debris on stream morphology and its role in creating and maintaining fish habitat has been demonstrated by numerous scientific papers since researchers began studying the interactions between debris and channel morphology nearly three decades ago (Thomson 1991). Prior to that time, in-stream debris was commonly viewed as a resource to be exploited and an impediment to fish migration rather than material that contributed to the health and productivity of aquatic systems (Sedell and Luchessa 1982).

Historic forest management practices have decreased the quantity and quality of large woody debris in streams throughout the Pacific Northwest (Bragg and Kershner 1999). Splash damming, salvage of in-stream wood, and active stream "clean-out" of both stable and logging-related debris have reduced the frequency of large woody debris from historic levels. In addition, clearcutting of riparian forests has resulted in smaller piece size and lower recruitment rates (Grette 1985, Bilby and Ward 1991). Recognizing these effects, policymakers in Washington state enacted regulatory requirements during the 1980s that required the retention of streamside buffers (i.e., areas with uncut trees) during logging operations on state and privately owned forestlands to provide for large woody debris recruitment and shade to regulate water temperatures. Later, during the early 1990s, watershed analysis produced management prescriptions for some basins which resulted in larger buffers to provide increased wood recruitment. Currently, policymakers are considering further restrictions on harvesting adjacent to streams in response to recent salmon stock listings under the federal Endangered Species Act (ESA) and increased pressure to comply with federal Clean Water Act standards.

To date, there has been no comprehensive effort to evaluate the effectiveness of Washington's regulatory buffer requirements in providing for large woody debris recruitment to streams. Previous research in the Pacific Northwest has provided information related to debris recruitment from intact riparian forests (Murphy and Koski 1989, McDade et al. 1990) as well as predictions of wood inputs using probabilistic models (VanSickle and Gregory 1990, Robison and Beschta 1990). However, none of these studies have evaluated the quantity and/or quality of large woody debris recruited from streamside buffers.

In this study, our primary objective was to evaluate the effectiveness of streamside buffers established in accordance with watershed analysis prescriptions in recruiting large woody debris to adjacent stream channels. To accomplish this, stream and riparian stand characteristics were surveyed at 10 recently harvested sites in the North Cascades region of Washington state. We evaluated effectiveness by comparing current debris frequency and size conditions to targets found in Washington's Forest Practices Board Manual for Conducting Watershed Analysis (hereafter referred to as "Board Manual") (1997) and Bilby and Ward (1989). Board Manual targets for woody debris frequency and size (also known as "resource condition indices") have been used to assess fish habitat quality as part of Washington state's Watershed Analysis process. The Board Manual provides numeric targets which translate into qualitative ratings for habitat quality (i.e., "poor", "fair" and "good"). Data from Bilby and Ward (1989) was also used to establish target conditions for evaluating buffer effectiveness. They developed channel width-dependent regression relationships for debris frequency and size using data from streams bordered by unmanaged, old-growth conifer-dominated forests in western Washington. In their report, Peterson et al. (1992) recommend the use of Bilby and Ward (1989) as one approach to evaluating salmonid habitat since this study represents one of the most complete data sets for unmanaged Washington streams. Using the Board Manual and Bilby and Ward targets, we tested the hypothesis that debris characteristics at our study sites are not significantly different from target conditions for debris frequency and size.

To further evaluate effectiveness, we compared debris recruitment among study sites to determine the effect of buffer width on wood loading. Sites were grouped into three categories based on average buffer width on one side of the stream (<20 m, 20 to 30 m, and >30 m). We tested the hypothesis that recruitment frequency (i.e., pieces recruited per unit stream length) did not differ significantly between the three buffer width classes.

A secondary objective was to evaluate the Riparian Stand Survey (Smith 1998) developed by the Timber, Fish and Wildlife Cooperative Monitoring and Evaluation Research Committee (CMER) and make recommendations for improving the methods. The methods were developed in an effort to establish a consistent approach to (1) inventorying and monitoring riparian forest conditions on a statewide basis, and (2) to gather information to evaluate the effectiveness of forest practices across a range of stream, vegetative, and topographic conditions. This project represents the first broad scale implementation of these survey methods.

STUDY SITE SELECTION

Large woody debris, stream channel and streamside buffer characteristics were documented at 10 sites in the North Cascades physiographic province of northwest Washington. The sites were distributed across five Watershed Administrative Units (WAU) where watershed analysis large woody debris prescriptions had been implemented as part of timber harvest operations between 1993 and 1997. Study sites were selected from a pool of potential sites where large woody debris prescriptions had been implemented as part of a harvest practice. To identify these sites, approved forest practice applications in the Deer Creek, Hansen, Hazel, Hutchinson, Jordan-Boulder, Lake Whatcom, Skookum, Tolt, and Griffin/Tokul WAUs were reviewed. A total of 49 potential study sites were identified. These sites were then stratified according to two stream gradient and three buffer width classes (Table 1).

Table 1. Number of timber harvest practices implemented in accordance with large woody debris prescriptions established through watershed analysis in the North Cascades region, stratified by channel gradient and streamside buffer width (total = 49 harvest practices in five Watershed Administrative Units).

	Buffer Width Class		
Gradient Class	<20 m	20-30 m	>30 m
0-8%	2	20	4
>8%	15	8	0

Ten sites were randomly selected from four of the six strata (1 site = <8%, <20 m; 1 site = >8%, <20 m; 3 sites = <8%, 20-30 m; 2 sites = >8%, 20-30 m; 3 sites = <8%, >30 m). Selected sites were field checked to ensure buffers complied with prescriptions and actual channel gradients agreed with mapped gradients. Several sites were rejected because they had not been harvested at the time of site review. All sampling sites were required to be at least 75 m in length and located entirely within a single watershed analysis stream segment to ensure relatively homogenous stream channel characteristics (e.g., bankfull width, gradient, confinement, and flow). The upstream and downstream limits of the study site coincided with timber harvest boundaries except where a distinct change in channel morphology occurred. In cases where the study reach included more than one channel segment, the longer of the two segments was selected for evaluation.

Streams ranged from second to fourth order, average bankfull channel widths ranged from 2.1 to 8.1 m, and channel gradients ranged from 0.015 to 0.226 m/m (Table 2). Buffer basal areas ranged from 37.8 to 76.6 m^2/ha. Sites were located at low elevations (<400 m) where soils have formed atop glacial deposits (Pessl et al. 1989, Booth 1990).

Streamside buffers were generally conifer-dominated and typical of second-growth, even-aged forests in the region. Half the study sites had buffers on one side of the stream while the remainder had buffers on both sides (Table 2). Of the five sites where buffers were present on only one side of the stream, four had intact second-growth forest on the opposite side; the remaining site was bordered by a buffer established under earlier forest practices regulations. No harvesting had occurred within any of the buffers and all adjacent harvest units were clearcut. Average buffer widths ranged from 16.4 to 38.8 m horizontal distance on one side of the stream (Table 2). Western hemlock (*Tsuga heterophylla*) and Douglas-fir (*Pseudotsuga menziesii*) were the dominant tree species; western redcedar (*Thuja plicata*), red alder (*Alnus rubra*), bigleaf maple (*Acer macrophyllum*) and Pacific silver fir (*Abies amabilis*) were present at most sites (Table 3). Average diameter at breast height (DBH) ranged from 25 to 35 cm (Table 3).

Table 3. Tree species composition and average diameter at breast height (DBH) for 10 second-growth streamside buffers in the North Cascades (percentages do not total 100 due to exclusion of minor species comprising <1 percent of total).

	Tree Species Composition (%)[1]						
Site	TSHE	PSME	THPL	ALRU	ABAM	ACMA	Mean DBH (cm)
King	27	4	30	30	0	9	34.8
Brannian	20	6	19	51	0	0	32.1
Edfro	34	40	18	7	1	0	29.1
Deer Fly	70	1	4	2	23	0	26.1
South Deer	61	1	6	25	4	0	25.1
Lynch	66	32	0	1	0	0	28.1
Crazy West	41	48	0	11	0	0	34.5
Crazy East	31	11	0	57	0	0	29.3
Upper Griffin	39	22	29	8	0	2	34.4
East Fk Griffin	32	44	1	9	0	14	30.9

1 - Species Codes: TSHE = western hemlock; PSME = Douglas-fir; THPL = western redcedar; ALRU = red alder; ABAM = Pacific silver fir; ACMA = bigleaf maple

Table 2. Watershed Administrative Unit (WAU) and physical characteristics of 10 study sites used to evaluate the effectiveness of streamside buffers in providing large woody debris recruitment to streams in the North Cascades, Washington.

Site	WAU	Mean buffer width (m)	N-sided buffer (½)	Mean channel gradient (m/m)	Mean channel width (m)	Buffer basal area (m^2/100m)[1]	Buffer basal area (m^2/ha)[2]	Channel length (m)
King	Lake Whatcom	16.4	2	.057	2.1	7.7	47.3	489
Brannian	Lake Whatcom	20.6	1	.058	5.5	12.7	61.7	502
Edfro	Skookum	25.5	1	.101	5.1	19.6	76.6	385
Deer Fly	Deer Creek	24.9	2	.097	6.1	16.1	64.3	565
South Deer	Deer Creek	17.6	2	.226	6.4	9.2	52.3	392
Lynch	Tolt	38.8	1	.015	5.9	22.7	58.7	700
Crazy West	Tolt	32.0	1	.039	8.1	21.5	67.3	473
Crazy East	Tolt	27.4	1	.018	7.4	12.9	47.0	390
Upper Griffin	Griffin/Tokul	24.6	2	.075	5.1	12.8	51.9	401
East Fk Griffin	Griffin/Tokul	36.1	2	.027	4.2	14.1	37.8	420

1 - Basal area expressed as square meters per 100 meters of stream length
2 - Basal area expressed as square meters per hectare of buffer area

METHODS

Field Measurements

Standard TFW monitoring methods were used to collect data for the project, including the TFW Riparian Stand Survey (Smith 1998) and TFW Large Woody Debris Survey (Schuett-Hames et al. 1994). Riparian stand conditions were documented in 30 m long plots distributed at 120 m intervals along the length of the study reach. Plots extended from the bankfull channel edge outward to the buffer/harvest edge. As such, plot width and area varied with buffer width and hillslope gradient. All distance measurements were converted to horizontal distances prior to data analysis. The buffer/harvest edge was defined as half the distance from the outermost buffer trees to the nearest harvested trees. Outer plot corners were permanently monumented to facilitate future inventory.

Buffer width, hillslope gradient, and channel orientation were measured at each plot. All standing live trees >10 cm diameter at breast height (DBH; measured at 1.37 m above the ground) and standing snags (>10 cm and 1.37 m height) in decay classes 1-3 were inventoried. Species, DBH (or diameter at harvest height for trees cut below breast height), distance from bankfull channel, condition class, and decay class were recorded for each tree/snag.

Down wood, including both trees and broken pieces, were inventoried at each plot. Down trees were defined as those trees which 1) no longer supported their own weight, 2) had an attached rootwad, and 3) DBH >10 cm. Down trees inventoried included those in decay classes 1-3 whose point of origin could be identified as inside the plot. Species, DBH, decay class, fall direction, recruitment class, distance from bankfull channel, and number of associated broken pieces were recorded for each down tree. Broken pieces were defined as down wood which did not qualify as a down tree and whose midpoint diameter and length were >10 cm and > 2 m, respectively. Broken pieces were inventoried only if the source tree was located inside the plot. Source tree, diameter at midpoint, and recruitment class were recorded for broken pieces.

Channel gradients and bankfull widths were measured at 30 m intervals along the entire length of the study reach. Dominant substrate type was also characterized at these same locations. Within each study reach, all large woody debris pieces (defined as >2 m in length and >10 cm diameter) and rootwads (defined as <2 m in length and >20 cm diameter) located within the bankfull flow zone and/or suspended above the channel were inventoried. The midpoint diameter and length of each piece/rootwad was recorded and the proportion of volume within each of four influence zones was estimated (Robison and Beschta 1990). The four influence zones included the following portions of the cross-sectional channel area: the zone under water at the time of the survey, the zone between the current and bankfull flows, the zone above the bankfull flow but between the bankfull channel margins, and the zone outside any of the aforementioned zones (i.e., upland zone). Debris was also classified by species, decay class, and stability. Decay classes were based on the five class system developed by Maser and Trappe (1984) and later modified by Robison and Beschta (1991).

Log jams were defined as accumulations of 10 or more qualifying debris pieces and/or rootwads and were inventoried by tallying the number of pieces and/or rootwads in the jam in each of four size categories. As noted previously, rootwads were defined as debris >20 cm at the root collar and < 2 m long. Small debris pieces were defined as those between 10 and 20 cm at midpoint diameter, medium debris pieces were 20 to 50 cm at midpoint diameter, and large debris pieces were >50 cm at midpoint diameter. Each log jam was classified according to the lowest influence zone into which it intruded. Neither the proportion in each influence zone nor the decay class was documented for individual debris pieces comprising each jam.

Data analysis

The Pilot Project Monitoring Plan (PPMP) for this study described several hypotheses to be tested in the evaluation of streamside buffer effectiveness relative to woody debris recruitment (Smith et al. 1998). Those hypotheses were as follows:

1) The riparian stand density, species composition, and diameter distribution where riparian prescriptions have been implemented within the past five years are not significantly different from the targets established by the prescriptions and are not significantly different from conditions in reference stands of the same age.
2) The in-channel LWD loading (pieces per channel width and volume of key pieces) within five years after harvest is not significantly different from the watershed analysis resource condition indices for LWD, and the number, volume, and function of in-channel LWD pieces are not significantly different from conditions in reference stands of the same age.
3) The trend in stand and channel conditions over several decades is significantly different from zero and is moving in the direction indicated by reference stands in several age classes.
4) The performance of several different types of practices (i.e., three different buffer widths) carried out on stream reaches with a variety of channel characteristics are not significantly different from one another.

While we have addressed portions of each of these hypotheses through our data analysis, we were unable to fully test Hypotheses #1 and #2. Hypothesis #1 refers to stand density, species composition, and diameter distribution and suggests the data analysis will attempt to determine if these parameters are significantly different from "...targets established by the (watershed analysis) prescriptions...". The assumption behind this hypothesis was that prescriptions explicitly stated target conditions for these parameters; however, this proved to be incorrect. All prescriptions evaluated as part of this study relied wholly on buffer width as a performance standard rather than measures of stand density, species composition, or diameter distribution. Therefore, our test of Hypothesis #1 was limited to whether or not the buffers met the width targets required by the watershed analysis prescriptions. Similarly, Hypothesis #1 suggests the data analysis will compare density, composition, and diameter distribution at our study sites with "reference stands of the same age". The original intent was to identify unmanaged reference sites that could be used as a basis for comparing various stand and in-stream parameters and thus evaluate effectiveness. These reference sites would be comparable to our study sites in terms of forest age and species composition as well as channel characteristics (e.g., width, gradient, and confinement). Due to budget and time limitations, we were unable to identify and inventory reference stands and as a result, were unable to conduct the comparative analysis originally intended as part of Hypothesis #1.

While we addressed part of Hypothesis #2 by comparing debris frequency and size characteristics at our study sites with the watershed analysis resource condition indices, we did not compare debris characteristics relative to reference stands since we did not, as noted above, inventory reference stands as part of the project. However, we did conduct a comparative analysis of debris characteristics at our sites with those of Bilby and Ward (1989) as previously discussed. Since the sites inventoried by Bilby and Ward were bordered by unmanaged stands, the channel-width dependent relationships developed from their data represent conditions we might expect to see in reference stands. However, one important difference between our sites and those of Bilby and Ward is stand age. While our hypothesis indicates reference stands will be of the same age as the study sites, the streams inventoried by Bilby and Ward were bordered by "...undisturbed old-growth forest..." and were therefore much older than the second-growth managed stands we evaluated.

In the absence of reference stand data, we modeled forest stand growth to evaluate the trend in stand and channel conditions relative to debris recruitment (Hypothesis #3). We assumed the Bilby and Ward target conditions for debris diameter were acceptable surrogates for reference conditions. Using published growth curves or stand tables we estimated the time necessary for the current streamside buffer to recruit debris equal to the Bilby and Ward (1989) target diameter.

Hypothesis #4 was tested by comparing debris recruitment between three buffer width categories (<20 m, 20-30 m, >30 m). We evaluated recruitment frequency (expressed as pieces recruited per unit stream length) and debris source distance relationships (see McDade et al. 1990) to determine the extent to which buffer width influenced recruitment.

In order to evaluate buffer effectiveness, it was necessary to distinguish between debris recruited from the buffer since the time of harvest and debris recruited prior to buffer establishment. Field observations indicate most debris recruited prior to buffer establishment originated from the previous (original) forest, although some pieces appeared to have been recruited from the current second-growth stand prior to the most recent harvest (i.e., prior to buffer establishment). To differentiate between debris recruited from the buffer and debris recruited from the previous forest, we used decay class as an indicator of time since recruitment. All study sites were harvested between 1993 and 1997, therefore time since buffer establishment ranged from two to five years. We assumed debris, down trees, and down wood in decay classes 1 or 2 originated from the buffer (i.e., two to five years since time of recruitment) while debris in decay classes 3 through 5 originated from the previous forest. Since decay class was not documented for log jams we were unable to distinguish between jam pieces recruited from the buffer and jam pieces recruited from the previous forest. As a result, much of the analysis is limited to non-jam pieces and rootwads.

We assumed the rate of debris input from upstream sources into the study reach was similar to the rate of debris exported from the study reach. In addition, for sites buffered on only one side of the stream, we assumed that a large majority of recently recruited debris originated from the buffer as opposed to the uncut forest stand on the opposite bank. Qualitative observations made during the field inventory indicate this assumption is reasonable.

Piece frequency was expressed both in terms of pieces/meter (Bilby and Ward 1989) and pieces/bankfull channel width (Washington Forest Practices Board Manual) (Table 4). Key piece frequency, which quantifies debris pieces which are independently stable and capable of retaining other debris pieces, was expressed in terms of pieces/bankfull channel width (Washington Forest Practices Board Manual) (Table 4). Geometric mean diameter and geometric mean length of debris pieces for each study site were calculated based on measurements of midpoint diameters and total lengths. An estimate of the average piece volume for each site, termed debris volume index (DVI) by Bilby and Ward, was made by calculating the volume of a cylinder whose dimensions were represented by the geometric mean diameter and geometric mean length. The geometric mean diameter, geometric mean length, and DVI for each study site were compared to targets derived from the channel width-dependent regression developed by Bilby and Ward (1989) (Table 4).

Table 4. Target parameters used in evaluating the effectiveness of streamside buffers in providing large woody debris to 10 streams in the North Cascades, Washington.

Target Parameter	Target Value Definition	Source[1]
Debris frequency (pcs/cw)	<1 = poor; 1-2 = fair, >2 = good	WFPBM
Key piece frequency (pcs/cw)	<0.15 = poor; 0.15-0.30 = fair; >0.30 = good	WFPBM
Debris frequency (pcs/m)	$\log_{10}$debris frequency = -1.12($\log_{10}$channel width) + 0.46	B&W
Geometric mean diam (cm)	mean diameter = 2.14(channel width) + 26.43	B&W
Geometric mean length (m)	mean length = 0.43(channel width) + 3.55	B&W
Debris volume index (m^3)	debris volume index = 0.23(channel width) - 0.67	B&W

1- WFPBM = Washington Forest Practices Board Manual (1997)
B&W = Bilby and Ward (1989)

RESULTS/DISCUSSION

Buffer Width

Average buffer widths exceeded target widths established by watershed analysis prescriptions at all 10 sites (Table 5). The degree to which actual widths exceeded targets ranged from 2 to 93 percent, with the largest exceedances generally occurring at locations where slope stability issues led to the retention of wider buffers on steeper, stream-adjacent slopes (e.g., Edfro and South Deer). At the Lynch Creek study site, unstable slopes were not present, yet the actual buffer width exceeded the target width by a large margin (27 percent). According to personnel from Weyerhaeuser Corporation, the landowner at this site, the retention of a wider buffer was negotiated with the City of Seattle due to concerns over the protection of the city's domestic drinking water supply (pers. comm., Julie Sackett, Weyerhaeuser Corporation). The buffer at the Crazy East site also exceeded the target by a significant amount (29 percent). The reason for the wider buffer is unclear, although it may be related to the unconfined nature of the channel in some locations. Oftentimes, the exact location of the ordinary high water mark (OHWM), used to define the point at which the buffer begins, is difficult to discern in low-gradient, unconfined channels. Differences between how the landowner, versus the project survey crew, delineated the OHWM may be one explanation for the width exceedance.

Table 5. Measured and target buffer widths (one side of stream) for 10 second-growth streamside buffers in the North Cascades, Washington (target values based on requirements established through the watershed analysis prescription process).

Site	Measured (meters)	Target (meters)	Difference (%)
King	16.4	15.2	+8
Brannian	20.6	20.1	+2
Edfro	25.5	20.1	+27
Deer Fly	24.9	21.3	+17
South Deer	17.6	9.1	+93
Lynch	38.8	30.5	+27
Crazy West	32.0	30.5	+5
Crazy East	27.4	21.3	+29
Upper Griffin	24.6	21.3	+15
East Fk Griffin	36.1	30.5	+18

Buffer Mortality

While all study sites exceeded the targets for buffer width, post-harvest mortality, primarily associated with wind damage, significantly reduced stand density at several locations. Post-harvest buffer mortality ranged from 2.9 to 56.8 percent of stand basal area and 4.8 to 60.5 percent of stem density (Table 6). Qualitative observations conducted during the field inventory suggested most of this mortality was due to wind damage, either in the form of uprooting, stem breakage, or toppling as a result trees being hit by adjacent falling trees. Several researchers have documented high levels of windthrow in streamside buffers throughout the Pacific Northwest (Steinblums et al. 1984, Andrus and Froehlich 1990; Grizzel and Wolff 1998). While in unmanaged forests, windthrow is one of several mechanisms by which woody debris is recruited to stream channels (Keller and Swanson 1979), windthrow is typically the primary mechanism of wood delivery in managed forests where streamside buffers are often adjacent to clearcut harvest units.

Table 6. Proportion of standing live, standing dead, and down dead trees in 10 second-growth streamside buffers in the North Cascades, Washington two to five years following adjacent clearcut harvest.

	Standing Live		Standing Dead		Down Dead		Buffer Mortality[1]	
Site	(m^2/100m)[2]	(trees/100m)[3]	(m^2/100m)	(trees/100m)	(m^2/100m)	(trees/100m)	(%BA)	(%stems)
King	6.97	53.8	0.48	2.6	0.24	2.5	9.4	8.7
Brannian	12.31	100.0	0.32	10.6	0.10	5.6	3.3	13.9
Edfro	17.33	182.2	1.11	26.6	1.13	27.8	11.4	23.0
Deer Fly	13.67	196.3	1.93	32.5	0.47	11.7	14.9	18.4
South Deer	7.01	117.2	1.15	17.2	1.03	25.0	23.7	26.5
Lynch	18.04	210.7	2.75	55.4	1.95	25.3	20.7	27.7
Crazy West	15.35	127.5	4.38	43.4	1.82	22.5	28.8	34.1
Crazy East	12.54	153.3	0.27	3.3	0.10	4.4	2.9	4.8
Upper Griffin	5.53	50.4	3.12	24.6	4.16	52.5	56.8	60.5
East Fork Griffin	12.57	125.8	1.04	19.2	0.48	13.3	10.8	20.5

1 - Buffer mortality includes standing dead and down dead trees.

2 - density expressed as tree basal area per 100 meters of buffer length.

3 - density expressed as number of trees per 100 meters of buffer length.

In-Stream Debris Frequency

Resource Condition Indices - The Board Manual provides a number of resource condition indices for describing fish habitat quality as part of the watershed analysis process. The indices for large woody debris are based on the frequency of debris pieces lying within the bankfull flow zone. One index utilizes the number of debris pieces per channel width while the other relies on the number of "key" pieces per channel width. Key pieces are distinguished from other debris based on their larger diameter, length, and/or volume.

Table 7 reports debris piece frequencies, key piece frequencies and corresponding habitat quality ratings for the 10 study sites. The values reported include all debris (wood recruited from the buffer as well as the previous forest stand) intruding into the bankfull flow zone. In cases where debris jams intruded into the bankfull flow zone, all pieces contained in the jam counted toward the frequency total.

Based on debris piece frequency, habitat quality at nine of 10 sites rated as "good" while one site rated "poor" (Table 7). However, when using key piece frequency as an index of habitat quality, only four sites rated "good" while five sites rated "fair" and one "poor". This indicates that while these sites may have a sufficient number of small to moderate sized debris pieces, some lack larger, more stable debris necessary to function as key pieces. Of the 63 non-jam debris pieces that qualified as key pieces, 86 percent were in decay class 3, 4, or 5 (decay class was not recorded for jam pieces). This suggests a large majority of key pieces are remnant pieces that originated from the previous forest and were not recruited from the current streamside buffer.

Bilby and Ward - Debris frequency was also calculated as the number of debris pieces per meter of stream length so as to be comparable to the channel-width dependent frequencies reported by Bilby and Ward (1989) (see Table 4). As mentioned previously, we did not collect decay class information for jam pieces. As a result, reported debris frequency values include all pieces (both jam and non-jam) that intrude into the bankfull flow zone irrespective of their time of recruitment.

Based on debris frequency values derived from the Bilby and Ward equation, debris frequency exceeded target levels at seven of 10 study sites (Table 8). Measured piece counts ranged from 0.15 to 1.06 pieces/meter. One of the three sites below target, King Creek, rated "poor" according to the Board Manual resource condition indices while the other two sites, Lynch Creek and East Fork Griffin Creek, received "good" habitat quality ratings (see Table 7). It should be noted that the Lynch and East Fork Griffin sites are only marginally below the Bilby and Ward target compared to the King site, which is well below all debris frequency targets (Tables 7 and 8).

Table 7. Debris piece frequency, key piece frequency, and corresponding habitat quality ratings[1] for 10 streams bordered by second-growth streamside buffers in the North Cascades, Washington.

Site	Debris Piece Frequency (pcs/cw)	Habitat Quality Rating[2]	Key Piece[3] Frequency (pcs/cw)	Habitat Quality Rating[4]
King	0.22	POOR	0.04	POOR
Brannian	2.56	GOOD	0.21	FAIR
Edfro	4.56	GOOD	0.24	FAIR
Deer Fly	3.29	GOOD	0.19	FAIR
South Deer	6.49	GOOD	0.66	GOOD
Lynch	2.01	GOOD	0.16	FAIR
Crazy West	6.24	GOOD	0.26	FAIR
Crazy East	4.98	GOOD	0.45	GOOD
Upper Griffin	5.45	GOOD	0.68	GOOD
East Fk Griffin	2.22	GOOD	0.54	GOOD

1 - Habitat quality ratings are from the Fish Habitat Module, Washington Forest Practices Board Manual for Conducting Watershed Analysis (Washington Forest Practices Board, 1997)

2 - Habitat quality ratings for debris piece frequency are as follows: <1 piece/cw = poor; 1 to 2 pieces/cw = fair; >2 pieces/cw = good

3 - Key pieces are defined as follows: for channels with bankfull widths 0 to 5 meters, key pieces are ≥40 cm in at midpoint diameter and ≥8 meters in length OR ≥1 $meter^3$ in volume; for channels with bankfull widths 6 to 10 meters, key pieces are ≥55 cm at midpoint diameter and ≥10 meters in length OR ≥2.5 $meters^3$ in volume

4 - Habitat quality ratings for key piece frequency are as follows: for channels with bankfull widths < 10 meters: <0.15 pieces/cw = poor; 0.15 to 0.30 pieces/cw = fair; >0.30 pieces/cw = good

Table 8. Debris frequency for large woody debris in 10 streams bordered by second-growth streamside buffers in the North Cascades compared to targets derived from streams adjacent to unmanaged stands in western Washington (after Bilby and Ward 1989). Debris in streams bordered by second growth stands includes both individual and jam pieces but does not distinguish between debris recruited from the buffer and debris recruited prior to buffer establishment.

Site	Measured (pcs/m)	Target[1] (pcs/m)	Difference[2] (pcs/m)	Buffer Origin[3] (%)
King	0.10	1.26	-1.16	18
Brannian	0.46	0.43	+0.03	5
Edfro	0.89	0.47	+0.42	16
Deer Fly	0.54	0.38	+0.16	9
South Deer	1.02	0.36	+0.66	8
Lynch	0.34	0.40	-0.06	38
Crazy West	0.77	0.28	+0.49	12
Crazy East	0.68	0.31	+0.37	4
Upper Griffin	1.06	0.47	+0.59	24
East Fk Griffin	0.53	0.58	-0.05	15

1 - Target calculated according to: $\log_{10}$debris frequency = -1.12($\log_{10}$channel width) + 0.46 (Bilby and Ward 1989)

2 - Difference = (measured piece frequency - target piece frequency)

3 - Percent of non-jam pieces recruited from the buffer post-harvest; these are minimum percentages since jam pieces are not included in the calculation.

At several sites, debris frequency had been significantly increased due to buffer windthrow. The extent to which windthrow of buffer trees contributed to the total debris load was based on the number of non-jam pieces in decay classes 1 and 2. At Lynch and Upper Griffin, two sites that experienced relatively high levels of buffer mortality, buffer recruitment accounted for at least 38 percent and 24 percent of the total debris load, respectively (Table 8). Actual buffer recruitment is likely higher since jam pieces recruited from buffers are not reflected in the percentages.

In-Stream Debris Distribution

In addition to analyzing debris frequency, we evaluated the degree to which in-stream debris influenced fluvial processes. Generally, fewer buffer debris pieces intruded into the bankfull flow zone relative to debris recruited from the previous forest (Figure 1). The proportion of buffer debris pieces intruding into the bankfull zone (zones 1 and 2) averaged 38 percent across the 10 sites as compared to 82 percent for older debris. These findings are consistent with those of Ralph et al. (1993) where 67 percent of woody debris pieces in unlogged basins of western Washington were located within the low-flow wetted channel width while 46 percent and 31 percent of pieces in basins with moderate and intensive levels of timber harvest, respectively, were found within the same zone. The authors attributed this relationship to decreased hydraulic stability associated with smaller debris pieces originating from second growth forests and suggested that smaller pieces are more prone to mobilization and transport during higher streamflows.

Much of the debris recruited at our sites is in the form of whole trees that did not break apart when they fell to the ground. As a result, much of this material is suspended above or spanning the channel with the majority of debris volume lying in the upland zone (zone 4). Over time, these trees will decay and portions suspended above the channel may break and deposit within the bankfull zone. The degree to which these pieces function once they reach the channel will depend on their size and state of decay; smaller pieces are less likely to be of functional size and may be in a more advanced state of decay compared to larger tree boles. While many of these pieces are currently stable, smaller piece size following decay and breakage may render these pieces more prone to mobilization and transport during high streamflows.

In-Stream Debris Size

Debris Recruited From Streamside Buffers - We compared the geometric mean diameter, geometric mean length, and debris volume index of buffer debris with target values derived from the channel-width dependent regression equations from Bilby and Ward (1989).

Geometric mean diameters for debris recruited from streamside buffers (i.e., pieces in decay classes 1 and 2) were below target values at all sites (Table 9). Mean diameters ranged from 6.2 to 25.2 cm below target with the largest differences occurring at sites where bankfull widths were greatest. This suggests that second-growth buffers will begin contributing wood of target diameter sooner for smaller streams as compared to larger streams where target diameters are higher. Second-growth stands included in this study ranged from 45 to 60 years of age compared to more than 100 years for the unmanaged stands from which targets were derived. Therefore, the recruitment of smaller diameter debris from second growth streamside buffers is not unexpected.

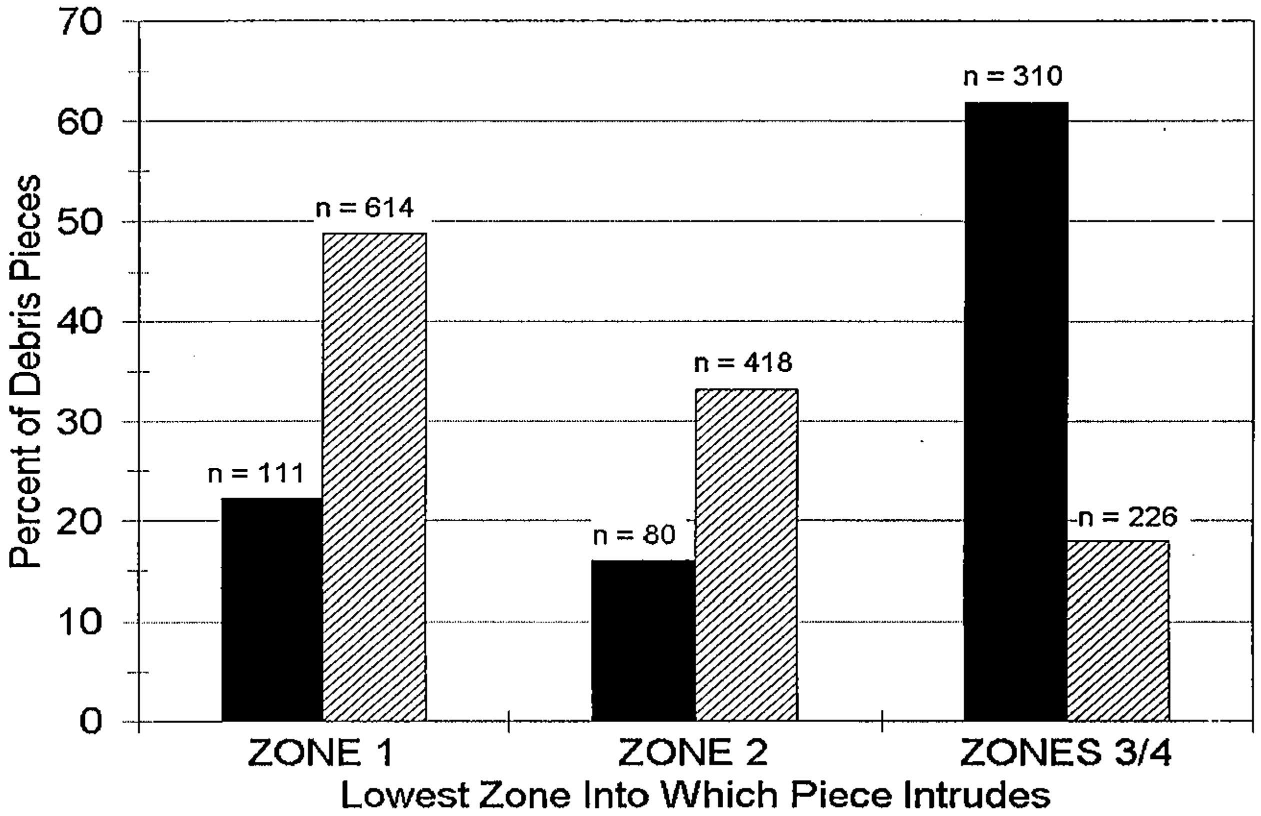

Figure 1. Spatial distribution of large woody debris relative to four channel influence zones (Robison and Beschta 1990) at 10 sites in the North Cascades, Washington. Black bars represent that portion of the total debris load recruited from streamside buffers since time of adjacent timber harvest; hatched bars represent that portion recruited from the previous forest stand.

Table 9. Geometric mean diameter, geometric mean length, and debris volume index for large woody debris pieces recruited from 10 second-growth streamside buffers in the North Cascades compared to targets derived from unmanaged old-growth stands in western Washington (Bilby and Ward 1989).

	Debris Diameter			Debris Length			Debris Volume Index		
Site	Measured (cm)	Target[1] (cm)	Difference[2] (cm)	Measured (m)	Target[3] (m)	Difference (m)	Measured (m^3)	Target[4] (m^3)	Difference (m^3)
King	24.7	30.9	-6.2	17.6	4.5	+13.1	0.84	-0.18	+1.02
Brannian	17.6	38.2	-20.6	14.9	5.9	+9.0	0.36	0.60	-0.24
Edfro	20.4	37.3	-16.9	12.9	5.7	+7.2	0.42	0.50	-0.08
Deer Fly	20.5	39.5	-19.0	16.5	6.2	+10.3	0.54	0.73	-0.19
South Deer	20.4	40.1	-19.7	16.6	6.3	+10.3	0.54	0.80	-0.26
Lynch	20.1	39.1	-19.0	14.7	6.1	+8.6	0.47	0.69	-0.22
Crazy West	20.0	43.8	-23.8	18.3	7.0	+11.3	0.57	1.19	-0.62
Crazy East	17.1	42.3	-25.2	12.3	6.7	+5.6	0.28	1.03	-0.75
Upper Griffin	23.6	37.3	-13.7	12.3	5.7	+6.6	0.54	0.50	+0.04
East Fork Griffin	19.2	35.4	-16.2	16.0	5.4	+10.6	0.46	0.30	+0.16

1 - Diameter target based on following equation (Bilby and Ward 1989): mean diameter = 2.14(channel width) + 26.43

2 - Difference = measured value - target value

3 - Length target based on following equation (Bilby and Ward 1989): mean length = 0.43(channel width) -- 3.55

4 - Volume target based on following equation (Bilby and Ward 1989): debris volume index = 0.23(channel width) - 0.67

The geometric mean length of non-jam pieces recruited from buffers, however, exceeded target values at all sites (Table 9). Mean lengths ranged from 5.6 to 13.1 m above target. Several factors may explain greater piece lengths at the second-growth study sites. First, many of the debris pieces recruited from buffers were intact downed trees. Since these trees have only recently died, decay and associated breakage is limited. As decay progresses and trees suspended above the channel break apart, average piece length will decrease. A second explanation for longer average pieces at our study sites may be related to differences in recruitment mechanisms between second-growth buffers and intact old-growth forest stands. Trees in second growth buffers are more susceptible to windthrow due to increased exposure following harvest of adjacent trees. Intact stands such as those inventoried by Bilby and Ward are probably less prone to windthrow but may be more vulnerable to other factors which predispose trees to mortality. In old-growth stands, recruitment often occurs as a result of senescence, where individual trees decay and incrementally break apart (branches and/or tops). As a result, branches and/or tops of trees may be recruited rather than whole trees, which results in shorter pieces. Another factor which may contribute to shorter piece lengths in old growth stands relates to tree size and structural integrity. Due to a greater mass and momentum associated with falling old-growth trees, they are more likely to break apart when they hit the ground compared to smaller second-growth trees. Also, older trees typically have a much higher degree of rot and/or defect, which further increases the likelihood of breakage.

The debris volume index of non-jam pieces recruited from buffers was below target levels at seven of the 10 study sites (range = 0.08 to 0.75 m^3 below target) (Table 9). In all cases, large piece lengths countered deficits in piece diameters, resulting in debris volume indexes that exceeded target levels at three sites (range = 0.04 to 1.02 m^3 above target). Average piece lengths are expected to decrease with time as much of the debris currently suspended or spanning the channel decays and breaks apart. As a result, debris volume indices for these sites will decrease and pieces that may now be relatively stable are likely to become more prone to mobilization in the future. This suggests that in the long-term, piece diameter may be the more important factor determining the stability of in-channel debris since changes in diameter are more likely to be chronic as opposed to the episodic changes in length brought about as a result of breakage.

Debris Recruited From the Previous Forest - Much of the current in-stream debris at our study sites was recruited from the riparian forest that preceded the current streamside buffer. Residual stumps at most sites indicate that the previous forest was generally dominated by large, mature conifers in excess of 100 years of age. Large woody debris recruited from these stands exhibited size characteristics different from debris of buffer origin. Generally, debris recruited from the previous forest was larger in diameter, shorter in length, and smaller in volume compared to debris recruited from buffers (Table 10). Mean diameter of old debris exceeded that of buffer debris by 7 to 75 percent at

Table 10. Size characteristics of large woody debris recruited from streamside buffers (Buffer) and previous forest stands (Old) at 10 sites in the North Cascades physiographic province of northwest Washington; represents non-jam pieces only.

	Mean Diameter (cm)		Mean Length (m)		Debris Volume Index (m^3)	
Site	Buffer[1]	Old[2]	Buffer[1]	Old[2]	Buffer[1]	Old[2]
King	24.7	22.1	17.6	5.4	0.84	0.21
Brannian	17.6	27.1	14.9	5.5	0.36	0.32
Edfro	20.4	22.8	12.9	5.1	0.42	0.21
Deer Fly	20.5	28.0	16.5	4.3	0.54	0.26
South Deer	20.4	24.5	16.6	5.0	0.54	0.24
Lynch	20.1	29.7	14.7	4.8	0.47	0.33
Crazy West	20.0	21.3	18.3	5.4	0.57	0.19
Crazy East	17.1	25.9	12.3	3.7	0.28	0.20
Upper Griffin	23.6	22.4	12.3	5.3	0.54	0.21
East Fk Griffin	19.2	33.6	16.0	4.8	0.46	0.42
AVERAGE	20.4	25.7	15.2	4.9	0.50	0.26

1 - "Buffer" includes debris in decay classes 1 and 2
2 - "Old" includes debris in decay classes 3, 4, or 5

eight of 10 study sites. Mean length and debris volume index of old debris, however, ranged from 57 to 70 percent and 9 to 75 percent lower, respectively, than buffer debris at all 10 sites. This suggests that the shape of old debris at our study sites is similar to that of debris from unmanaged stands in that their diameter:length ratio tends to be larger than for pieces recruited from second-growth buffers. However, average piece volume of old debris at our sites is well below targets derived from Bilby and Ward (1989). There may be several reasons for the small piece size of old debris. First, many streams flowing through managed, second-growth forests experienced salvage of in-channel debris as part of the original harvest. Salvage typically focused on larger, more economically valuable pieces resulting in smaller debris being left in the channel. In addition, historic yarding practices resulted in a high level of streambed and bank disturbance, often rendering previously stable debris more mobile during high streamflows.

The comparison between the size of debris recruited from buffers and targets derived from Bilby and Ward (1989) indicates that short-term post-harvest mortality occurring as windthrow is generally not beneficial since it results in debris pieces that are typically below target volume and reduces long-term recruitment potential. Continued monitoring of riparian stand dynamics will provide additional insight into the effectiveness of these buffers, however, the use of tree growth models may provide an estimate of the time required for these sites to produce wood of target size. Relating mean debris diameter to mean stand diameter across a range of riparian forest conditions could provide one estimate of how stand attributes influence the character of in-stream debris (i.e., stands of X diameter produced debris of Y diameter). This information, coupled with a stand growth model would provide an estimate of how future stand conditions might affect debris size and long term recruitment potential.

Forest Growth Modeling

The comparative analysis conducted thus far illustrates that while current in-stream debris frequency targets are generally being met, the size of debris recruited from streamside buffers is in most cases below target. Using stand and site information, we predicted the time required for current streamside buffers to produce debris of target diameter as previously defined (Bilby and Ward 1989).

Approach - We estimated the time required for stand DBH to equal the debris diameter predicted by the Bilby and Ward (1989) channel-width dependent regression equation (referred to as target diameter). We first determined site index (SI_{age}) for each species based on measured heights and ages at each site. For Douglas-fir, western redcedar, and western hemlock, we plotted measured height and age on height-at-age graphs and estimated SI_{100} by interpolation between published curves (Meyer 1937, McArdle et al. 1961, Smith 1987). We found a significant proportion of Pacific silver fir at one site, but no published curves for that species were available. Because it was mixed with western hemlock and had a similar average diameter, height, and age, we used the western hemlock-Sitka spruce data for that species (Meyer 1937). We did not have published curves for red alder, but relied on the growth curve in Beechie (1998) for that species in the Skagit River basin, supplemented with stand table information from Chambers (1974) to estimate SI_{50}.

We established the target diameter for each stand based on the relationship between debris diameter and channel width (Bilby and Ward 1989). We then plotted DBH at present age for both the average stand DBH and the DBH of dominants and co-dominants for each species on the published DBH-at-age curves. Where DBH currently meets or exceeds the target diameter, we noted the time to recruitment of target-sized debris as "over" (Table 11). Where DBH was less than the target diameter, we projected the DBH growth forward until it met the target for the stand. We then read the age at target from the graph and calculated the number of years until trees reached the target diameter. These estimates represent only those trees near the streambank, as debris from trees farther away will be smaller than target diameter due to taper of the bole. Therefore, the stand as whole will not produce target-sized debris until many years later.

Time To Target - The average stand age for all sites was 52 years, and age ranged from 45 to 58 years (Table 11). For Douglas-fir and western redcedar, the DBH of dominant and co-dominant trees was larger than the target diameter at all sites where those species were present. Average DBH was at or near target diameter for both species (Table 11) (the Edfro Creek site for western redcedar appears to be only suppressed trees, and was not considered in these results). Western hemlock was slightly smaller, with dominants and co-dominants usually above target diameter, but with three of 10 sites one to four years from target. Average DBH for western hemlock ranges from at target to 50 years from target, and averages 25 years from target across all sites. Pacific silver fir is similar to western hemlock at the one site where it was present, with dominants and co-dominants above target and the average DBH of the stand 26 years from target diameter. Red alder dominants and co-dominants are over target diameter at three of four sites, and are 15 years from target at the fourth site. The projections suggest that the average stand DBH at this fourth site will not reach target diameter. Chambers (1974) reported that maximum diameter growth is about 1 inch per decade after age 50, which is insufficient to reach target diameter before the stand senesces.

The preceding evaluation indicates that only trees near the stream will generally produce LWD of target diameter in approximately 25 years (i.e., when stand age reaches 75 years). However, trees farther from the stream will not attain target diameter until much later because the portion of the tree that reaches the stream will be much smaller in diameter than the DBH. Therefore, the buffer as a whole will not produce LWD of target diameter for one to two decades more (stand age 85 to 100 years).

Table 11. Time to recruitment of target sized large woody debris for 10 streamside buffers in the North Cascades, Washington. Target diameters were based on Bilby and Ward (1989) channel-width dependent regression equation for debris diameter (see Table 4). Stand DBH refers to average diameter at breast height for all trees >10 cm DBH; D&C DBH refers to average diameter at breast height for dominant and co-dominant trees only.

Site	King	Brannian	Edfro	Deer Fly	South Deer	Lynch	Crazy West	Crazy East	Upper Griffin	E Fk Griffin
Bankfull width (m)	2.1	5.5	5.1	6.1	6.4	5.9	8.1	7.4	5.1	4.2
Target diameter (cm)	30.9	38.2	37.3	39.5	40.1	39.1	43.8	42.3	37.3	35.4
Stand age (years)	55	51	58	50	53	50	45	56	49	52
Western hemlock										
Stand DBH (cm)	37	29	23	26	22	25	28	28	30	27
Stand years to target	over	11	44	26	50	36	19	29	3	9
D&C DBH (cm)	52	54	46	39	46	37	46	42	40	41
D&C years to target	over	over	over	1	over	4	over	1	over	over
Douglas-fir										
Stand DBH			38			35	41	52	36	
Stand years to target			over			7	5	4	over	over
D&C DBH			57			53	54	58	54	59
D&C years to target			over			over	over	over	over	over
Western redcedar										
Stand DBH	40	44	16						30	
Stand years to target	over	over	192						14	
D&C DBH	76	70	22						33	
D&C years to target	over	over	142						8	
Pacific silver fir										
Stand DBH				27						
Stand years to target				26						
D&C DBH				43						
D&C years to target				over						
Red alder										
Stand DBH	21	24			31			28		
Stand years to target	NA	NA			NA			NA		
D&C DBH	25	45			47			42		
D&C years to target	15	over			over			over		

Debris Recruitment

In addition to evaluating the quantity and quality of large woody debris recruited at our study sites, we also assessed the degree to which debris recruitment varied between sites, primarily as a function of buffer width. We stratified the 10 streamside buffers into three buffer width classes as described in the Study Site Selection section of this report. Within each class, we evaluated the influence of buffer width on recruitment characteristics.

Debris source distance is a concept that has been discussed by Murphy and Koski (1989) and McDade et al. (1990). These authors have used source distances to describe debris recruitment as a function of distance from stream or "source". The source distance relationship is often illustrated as a cumulative frequency distribution where a proportion of total debris pieces recruited to the stream (Y) is expressed as a function of distance from stream (X).

Source distances for debris recruited at the study sites since the time of buffer establishment are illustrated in Figure 2. The proportion of debris recruited to streams varied as a function of distance from stream and buffer width. In all three buffer width classes (<20 m, 20-30 m, >30 m), over 50 percent of debris originated from within 15 meters of the bankfull channel. However, 19 percent and 28 percent of debris pieces were recruited from beyond 20 meters of the streambank in the 20-30 m and >30 m classes, respectively. In the >30m class, 10 percent of recruitment originated beyond 30 meters from the streambank (Figure 2). These relationships illustrate that as buffer width increases, the proportion of the total debris load recruited from a particular distance decreases. In addition, the results indicate that debris is being recruited from the outer portions of the wider buffers which suggests that narrower buffers limit recruitment.

To further examine the effect of buffer width on recruitment characteristics, we calculated recruitment frequency, or the number of down trees and broken pieces recruited to the channel per 100 meters stream length, for each site. Average recruitment frequency for the 20-30 m and >30 m buffer width classes was the same at 14.3 trees/pieces per 100 meters while the <20 m class averaged 8.1 trees/pieces per 100 meters (Table 12). While higher recruitment occurred at the wider buffers, the relatively short time frame since buffer establishment as well as the large degree of inter-site variability in recruitment suggests these values may not accurately reflect the influence of buffer width on recruitment. It is more probable that differences in both inter-site and inter-class recruitment are associated with differences in buffer mortality, primarily driven by wind damage, than with buffer width.

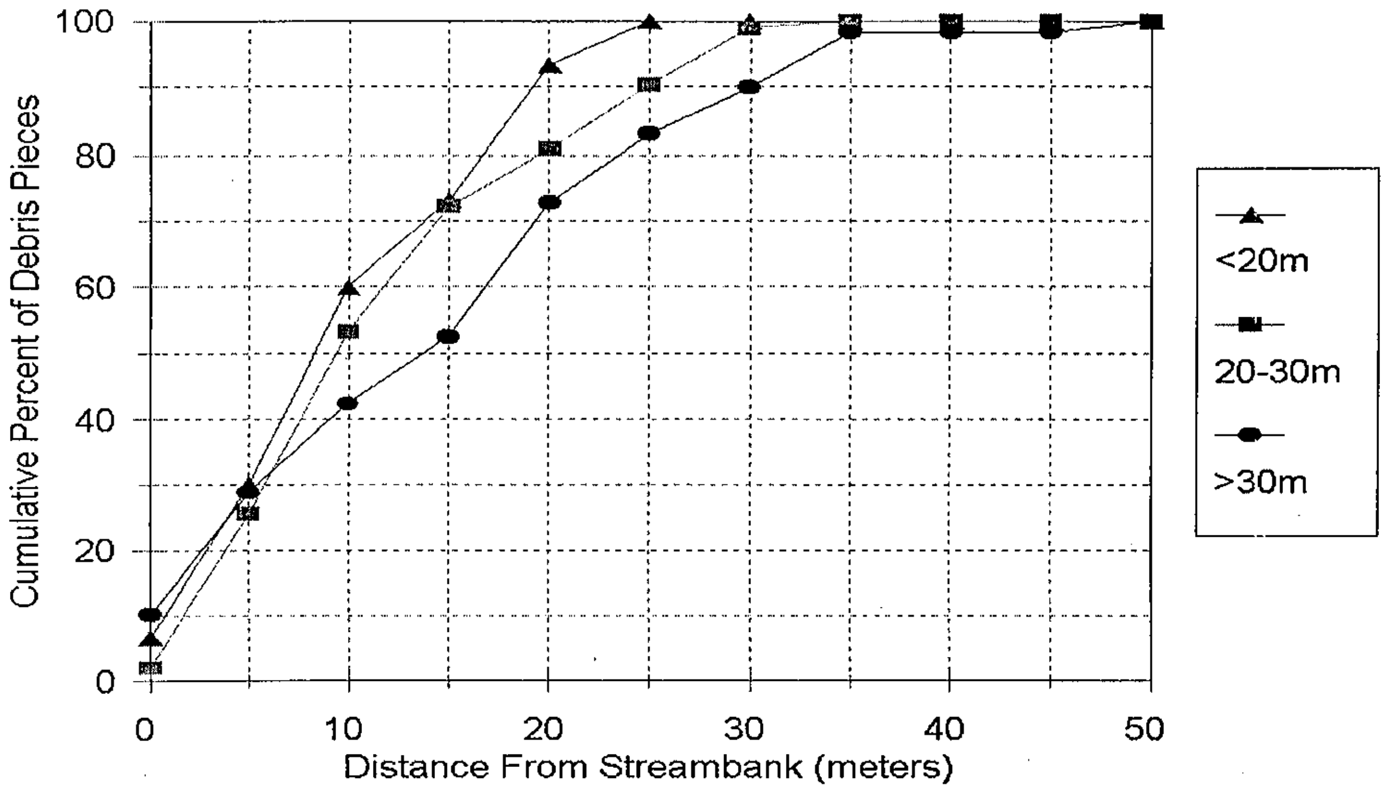

Figure 2. Distribution of source distances from origin to streambank for large woody debris recruited from streamside buffers averaging <20 m, 20-30 m, and >30 m on one side of the stream. Data collected from 10 second-growth buffers in the North Cascades, Washington.

Table 12. Large woody debris recruitment frequency (expressed as the number of down trees and broken pieces entering zones 1-3 per unit stream length) for debris recruited from 10 second-growth streamside buffers in the North Cascades, Washington.

Site	Buffer Width Class (m)	Number of Recruited Trees/Pieces	Surveyed Stream Length (m)	Recruitment Frequency (#/100 m)
King	<20	5	240	2.1
South Deer	<20	29	180	16.1
Class TOTAL	**<20**	**34**	**420**	**8.1**
Brannian	20-30	2	142	1.4
Crazy East	20-30	0	90	0.0
Deer Fly	20-30	8	240	3.3
Edfro	20-30	21	90	23.3
Upper Griffin	20-30	84	240	35.0
Class TOTAL	**20-30**	**115**	**802**	**14.3**
Crazy West	>30	31	120	25.8
East Fk Griffin	>30	16	240	6.7
Lynch	>30	26	150	17.3
Class TOTAL	**>30**	**73**	**510**	**14.3**

In addition to recruitment frequency, the proportion of down trees and broken pieces recruited to stream channels was compared between buffer width classes (Table 13). Data indicate that as buffer width increases, the proportion of broken pieces recruited to stream channels decreases. However, buffer width had little effect on the proportion of down trees reaching stream channels; approximately the same proportion of downed trees reached streams in the <20m buffer width class as in the >30m class (53 percent of downed trees versus 52 percent).

Table 13. Distribution of down wood (broken pieces and down trees) relative to channel influence zones by buffer width class for 10 second-growth streamside buffers in the North Cascades, Washington; influence zones 1-3 indicate piece/tree was in or above the bankfull flow zone while zone 4 indicates the piece/tree was wholly within the upland zone (N = number of pieces/trees, % = proportion of pieces/trees within the buffer width class).

	Broken Pieces		Down Trees	
Buffer Class	N Zones 1-3 (%)	N Zone 4 (%)	N Zones 1-3 (%)	N Zone 4 (%)
<20 m	7 (54)	6 (46)	27 (53)	24 (47)
20-30 m	29 (34)	57 (66)	86 (45)	105 (55)
>30 m	22 (24)	69 (76)	49 (52)	46 (48)

Previous research indicates the probability of a falling tree reaching the stream decreases with increasing distance from the stream (Robison and Beschta 1990, VanSickle and Gregory 1990). While our broken piece data reflects this trend, our down tree data does not. An explanation for the discrepancy between our down tree data and the published literature appears to be related to the non-random nature of tree fall direction at our study sites. Of the 391 down trees inventoried, 73 percent fell towards the northwest, north, and northeast (azimuth of 270° to 90°) and 35 percent fell towards the north (azimuth of 330° to 30°) indicating a non-random fall pattern influenced by southerly winds. Average tree fall direction at the three >30 m sites was offset 80° from the general stream orientation while average fall direction at the two <20 m sites was offset 35° from stream orientation. As the angle between stream orientation and tree fall direction decreases, the likelihood of a tree falling into or across the channel also decreases. Therefore, trees in buffers oriented perpendicular to the direction of damaging winds (i.e., east-west) have a higher likelihood of being recruited relative to buffers oriented parallel to damaging winds (i.e., north-south).

Other researchers have also documented non-random patterns of tree fall direction in western Washington (Mobbs and Jones 1995, Grizzel and Wolff 1998). Such information may be useful in modeling near-term post-harvest debris recruitment. However, developers of several quantitative debris recruitment models have assumed random tree fall directions (Robison and Beschta 1990, VanSickle and Gregory 1990) which may have limited applicability in areas where windthrow is the dominant recruitment mechanism. Knowledge of tree fall patterns may also prove beneficial during the timber harvest planning process. Land managers familiar with wind patterns may alter buffer configuration in attempt to maximize the probability of debris recruitment. For example, buffer width along the windward side of buffers may be increased in recognition that a higher proportion of recruited trees are likely to originate from that side of the stream. Prior to implementing such an approach, however, managers should consider the likelihood of those additional trees recruiting wood of functional size in the short-term. If the distance from the stream to the buffer's outer edge approaches the current or potential future effective height of those trees located along the outer edge, the likelihood of those trees providing functional wood in the short-term is relatively low (Robison and Beschta 1990).

CONCLUSIONS

All sites exceeded buffer width targets required by watershed analysis prescriptions. However, post-harvest mortality resulting from wind damage has substantially reduced stand density at several sites. In-stream debris frequency targets were met at most sites, however, key piece frequency rated "good" at only four of 10 sites. High levels of stand mortality will limit recruitment capacity at some sites which could reduce debris loading at some point in the future. Whether or not these sites continue to meet debris frequency targets in the future is a topic that can only be addressed through continued monitoring.

Currently, a large portion of the debris load recruited from buffers is above or outside the bankfull flow zone and is therefore not influencing fluvial processes. These pieces will likely recruit to the bankfull zone in the future, however, the degree to which they function once in the channel will be determined by their size and state of decay.

The size of debris recruited from buffers was significantly smaller than pieces recruited from unmanaged, old-growth stands. Although this does not mean these pieces will not provide the desired functions, it is likely they will not persist as long as larger, more stable pieces. Growth modeling suggests only trees in close proximity to the stream will reach target diameter within the next 25 years. Trees further from the stream will not produce target sized debris until age 85 to 100 (25 to 40 years from present).

Data show that recruitment is occurring from the outer margins of the widest buffers (20-30 m and >30 m) which suggests narrower buffers (i.e., <20 m) limit recruitment. While wider buffers had higher recruitment frequencies, the large degree of variability in recruitment from site to site suggests recruitment was more closely linked to windthrow levels than to buffer width. In the long term, however, wider buffers would be expected to produce higher recruitment frequencies simply because there are more trees available to recruit. Buffer orientation relative to the direction of damaging winds had a significant influence on the probability of debris recruitment. Trees in buffers oriented perpendicular to the direction of damaging winds (i.e., east-west) had a higher likelihood of being recruited relative to buffers oriented parallel to damaging winds (i.e., north-south).

This study demonstrates that short-term post-harvest debris recruitment from streamside forest buffers is heavily influenced by windthrow. The quantity and quality of debris recruited will be a function of windthrow magnitude, buffer orientation, and stand characteristics. From a fish habitat perspective, accelerated rates of windthrow should be minimized to maintain stand density and allow for the continued growth and development of streamside buffer trees. Ideally, debris recruitment from the buffer would mimic the natural or background rate to ensure a continuous supply of debris over the long term. In order to achieve these objectives, natural resource managers must gain a better understanding of the factors influencing windthrow patterns at local and regional levels and implement management practices aimed at minimizing its occurrence.

FUTURE STUDY

The following are recommendations for future study:

1) In order to determine the likely time required for current second-growth streamside buffers to produce large woody debris of target size, we recommend using quantitative models to predict forest growth and development. Forest Vegetation Simulator, or FVS (USDA 1996), is a multi-species growth model developed by the U.S. Forest Service that has been used in similar applications (Beechie 1998).

2) As part of this study, we assumed that large woody debris piece size and frequency could be used as an indirect measure of fish habitat quality. We recognize that much of the recently recruited debris, while contributing to the overall debris load, is outside the bankfull flow zone and has little effect on habitat formation. As a result, we recommend future effectiveness monitoring integrate a habitat inventory in order to relate habitat conditions to recruitment.

3) The fate of debris pieces suspended above stream channels is poorly understood. We assume that at some point in the future, these pieces will break apart, deposit in the stream, and provide some function. We also assume that the time required for this to occur is largely a function of debris size and species. Future study into the fate of these pieces will provide a more complete understanding of recruitment processes associated with streamside buffers. Additionally, continued monitoring of these sites will provide greater insight into longer-term buffer and debris dynamics and improve our understanding of the linkages between stand development, debris recruitment and habitat formation.

4) Generally, an accelerated rate of buffer windthrow following harvest is viewed as a process which may compromise riparian function. The degree to which various functions are affected is directly proportional to the magnitude of windthrow. High levels of windthrow may affect the buffer's capacity to produce functional-sized debris in the long

term. A better understanding of factors influencing windthrow, in addition to management techniques that reduce its occurrence, should be the focus of future study.

RIPARIAN STAND SURVEY METHODS

One goal of this project was to evaluate the approach used in accomplishing the objectives, so refinements could be made to the sampling methods developed for the TFW Cooperative Monitoring and Evaluation Research Program. The following items are resolutions of issues raised during the pilot project and represent recommended refinements to the Riparian Stand Survey developed by Smith (1998).

Sampling plots and strategy

The sampling strategy of sampling 25 percent of the lineal distance within the selected riparian reach should remain, however, the length of riparian plots should be changed from 30 m to 25 m. Plots will be placed at 100 m intervals along the survey reach. The 25 m plots will structure the data to be more compatible with other TFW monitoring methods, such as the Temperature and Reference Point surveys.

Regardless of the actual buffer width, plot widths should extend from the bankfull edge to a site potential tree height (approximately 40 m). The actual buffer width should also be recorded.

Standing trees

To avoid the confusion of common tree species names, species should be recorded with the four letter scientific code, rather than the two letter common name code (e.g., Douglas-fir = PSME).

Rather than recording the specific cause of mortality for dead trees, which can often be extremely difficult to determine in the field, mortality agents should be classified into four categories:

1) Harvest induced (H): includes mortality due to harvest related practices; hit by a logged tree, damage from machinery, sunscald (if surrounding trees have been harvested), or directly harvested;
2) Natural (N): includes mortality due to suppression, bank erosion, lightning, ice/snow damage, or animal damage;
3) Windthrow (W): includes mortality due to wind;
4) Unknown (U): includes mortality without clear evidence as to the causative agent.

To increase our ability to track changes over time, each standing tree within the plot should be tagged. Tags should be nailed into all inventoried trees at breast height on the upslope side of the tree.

In order to determine the site class for each site, the total height of the first tree for each species in each diameter class (10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm, 50-60 cm, 60+ cm) should be measured within each plot. Total age should also be recorded for each tree.

Down Wood

Individual broken pieces of down wood should be inventoried only if their source tree is/was rooted within the plot; regardless of whether the midpoint of the piece is within the plot boundaries. If a broken piece is completely outside the plot boundary, the piece should be inventoried if the source tree is/was rooted within the plot. If a broken piece lies entirely within the plot, but the source tree is rooted outside of the plot, the piece should not be inventoried.

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