Can. J. Fish. Aquat. Sci. Downloaded from www.nrcresearchpress.com by University of British Columbia on 01/24/13
For personal use only.

Characteristics and Function of Large Woody Debris in Streams Draining Old-Growth, Clear-Cut, and Second-Growth Forests in Southwestern Washington

Robert E. Bilby and James W. Ward

Weyerhaeuser Co., Technology Center 2H4, Tacoma, WA 98477, USA
and
Weyerhaeuser Co., Western Forestry Research Center, Centralia, WA 98531, USA

Bilby, R. E., and J. W. Ward. 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. Can. J. Fish. Aquat. Sci. 48: 2499–2508.

Amount of large woody debris (LWD) surveyed in 70 stream reaches flowing through old-growth, clear-cut, and second-growth forests decreased with increasing stream size for all stand types but was greatest at old-growth sites. Average piece volume was larger at old-growth sites than at other stand types in streams >10 m wide, but no differences were seen in smaller streams. Scour pools accounted for 90% of the wood-associated pools at second-growth and clear-cut sites but only 50% at old-growth sites, which contained more pools than other stand types, particularly for larger streams. Pool size was similar for all stand types in smaller streams, but averaged 10 m^2 in streams >10 m wide at old-growth sites and 4 m^2 for other stand types. Pool size was similar for all stand types in smaller streams. Sediment and fine organic matter retained by woody debris decreased with increasing stream size for all stand types, but old-growth sites contained greater amounts of both materials than other stand types. The frequency of pool formation, the type of pool formed, and sediment accumulation were influenced by the amount of fine debris associated with LWD. Changes in LWD amount, characteristics, and function occurred very rapidly following removal of streamside vegetation.

Les quantités de gros débris ligneux (GDL), étudiées dans 70 tronçons de cours d'eau s'écoulant dans de vieilles forêts, des forêts coupées à blanc et des forêts de seconde venue, ont diminué en fonction de l'augmentation de la taille des cours d'eau dans tous les types de peuplements, mais ce sont les vieilles forêts qui ont donné lieu aux quantités de GDL les plus importantes. Le volume moyen des débris présents dans les cours d'eau d'une largeur supérieure à 10 m a également été plus grand dans les vieilles forêts que dans les autres sites, mais dans le cas des cours d'eau plus étroits, on n'a pas observé de différence entre les trois types de peuplements. Les zones calmes d'affouillement représentaient plus de 90 % des zones calmes formées par les débris de bois dans les forêts de deuxième venue et les forêts coupées à blanc, mais seulement 50 % dans les vieilles forêts, qui comptent un plus grand nombre de zones calmes que les autres types de peuplements, surtout en ce qui a trait aux cours d'eau plus larges. La taille des zones calmes dans les petits cours d'eau était semblable dans tous les types de peuplements, alors que dans les cours d'eau de plus de 10 m de largeur, elle était en moyenne de 10 m^2 dans les vieilles forêts et de 4 m^2 dans les autres peuplements. Les sédiments et les matières organiques fines retenus par les débris ligneux ont diminué en fonction de l'augmentation de la largeur du cours d'eau dans tous les sites; toutefois, les vieilles forêts contenaient de plus grandes quantités de ces deux matériaux que les autres sites. La quantité de débris accompagnant les GDL a influé sur la fréquence de formation des zones calmes, le type de zones calmes et l'accumulation de sédiments. Des modifications de la quantité de GDL ainsi que de leurs caractéristiques et de leur rôle sont apparues très rapidement après l'élimination de la végétation riparienne.

Received November 27, 1990
Accepted June 12, 1991
(JA823)

Reçu le 27 novembre 1990
Accepté le 12 juin 1991

Large woody debris (LWD) controls many of the structural and functional properties of smaller streams in forested areas (Bilby and Likens 1980; Harmon et al. 1986; Bisson et al. 1987; Bilby and Ward 1989). Wood affects channel form through the formation and stabilization of pools, waterfalls, and gravel bars (Heede 1972; Bilby 1981; Lisle and Kelsey 1982; Lisle 1986). LWD influences sediment routing through the formation of depositional sites and the creation of waterfalls, which reduce the efficiency of downstream transport of particulate materials (Heede 1972; Swanson and Lienkaemper 1978; Beschta 1979; Bilby 1981; Megahan 1982). A large proportion of the standing stock of particulate organic matter in streams is often associated with LWD (Naiman and Sedell 1979; Bilby and Likens 1980). Wood also provides habitat for some invertebrates (Benke et al. 1984) and fishes (Bustard and Narver 1975; Bisson et al. 1982; Tschaplinski and Hartman 1983; Dolloff 1986; Elliott 1986; McMahon and Hartman 1989).

Features of the stream channel and the bordering riparian vegetation influence the amount and function of LWD. Channel size affects both wood amount and the relative influence of LWD on channel features (Swanson et al. 1976; Bilby 1979; Long 1987; Bilby and Ward 1989). Density of streamside trees is positively correlated with LWD amounts in some systems (Long 1987; Bilby and Wasserman 1989). Morphology of the bed may also influence LWD amount (Bilby and Wasserman 1989). Susceptibility of riparian trees to windthrow can play

Can. J. Fish. Aquat. Sci. Downloaded from www.nrcresearchpress.com by University of British Columbia on 01/24/13
For personal use only.

a major role in determining quantities of LWD in streams (Lienkaemper and Swanson 1987; Robison and Beschta 1990).

Various management activities in and adjacent to the channel have also influenced LWD amounts and characteristics in Pacific Northwest streams. Removal of wood from rivers for navigation or to provide upstream access for anadromous fishes has greatly reduced LWD amounts in some systems (Sedell and Luchessa 1982; Bilby 1984). Use of splash dams for log transport, a practice which was used widely in the Pacific Northwest until the 1950s, also reduced wood amounts in many streams (Wendler and Deschamps 1955). Removal of streamside timber during logging occurred until the early 1980s in the Pacific Northwest. While this practice no longer occurs, there are many streams where amount of LWD and the composition and structure of the riparian vegetation were influenced as a result of this activity.

Several conceptual models of the influence of streamside timber removal on amount of LWD have been developed (Swanson and Lienkaemper 1978; Likens and Bilby 1982; Grette 1985; Murphy and Koski 1989). In general, these models predict a decrease in LWD over time as a result of decay of wood present in the channel prior to disturbance coupled with decreased input from the riparian area.

Relatively few data have been collected to validate these models. Comparisons of the amount of LWD in streams flowing through old-growth and previously logged forests in several areas in the Pacific Northwest have verified the decrease in wood after removal of the streamside vegetation (Grette 1985; Long 1987). Some information is also available on the influence of stream size and channel characteristics on the rate of change in LWD amount after removal of streamside vegetation (Long 1987; Murphy and Koski 1989). However, little is known about the changes in the characteristics of pieces of LWD or their function over time after removal of streamside vegetation or the rate at which these changes occur. The purpose of this study was to compare LWD abundance, characteristics, and function in streams bordered by forests of differing ages: old-growth forest, recently clear-cut areas, and 40- to 60-yr-old second-growth forest. Comparison of the three stand age-classes provides an indication of the rate at which changes in LWD occur following timber removal from the riparian area.

Description of Study Sites

Measurements of LWD abundance, characteristics, and associated channel features were made on 70 stream reaches in southwestern Washington. All sites were located in the foothills of the Cascade Range or the Willapa Hills. Streams ranged from second order to fifth order with drainage areas from 0.4 to 137 km^2. Bankfull channel widths ranged from 3.1 to 23.5 m. All stream reaches surveyed drained watersheds underlain with volcanic bedrock (Huntting et al. 1961).

One of the most important factors in selection of the sites was the condition of the vegetation adjacent to the surveyed reach. Three stand-age classes were examined: (1) undisturbed, old-growth forest, (2) clear-cut to the channel's edge within 5 yr of the survey, and (3) second-growth forest which had been clear-cut to the edge of the channel 40–60 yr prior to our survey. The clear-cut and second-growth classes had been logged only once.

Sites where factors other than stream size and vegetative characteristics of the riparian zone were likely to have influenced LWD were not surveyed. Stream reaches which had been splash dammed at some time in the past were excluded (Wendler and Deschamps 1955). In addition, streams flowing through clear-cut areas which exhibited evidence of post-harvest channel cleaning were avoided, although selective removal of merchantable wood from the stream during or after logging could not be detected. We also avoided reaches which showed evidence of being influenced by landslides or debris torrents during the recent past.

Mean annual precipitation at the sites varied from 180 to 280 cm, primarily as a result of changes in elevation (Sternes 1969). However, all sites were located within 100 km of one another and thus were likely exposed to a relatively similar history of high discharge events, which play a major role in determining LWD distribution (Bilby 1984; Lienkaemper and Swanson 1987).

Methods

Aerial photographs were utilized to identify streams bordered by appropriate forest conditions. These sites were then examined on the ground to determine if they met the criteria outlined above. Once sites were located, watershed area above the surveyed reach was determined from U.S. Geological Survey topographic maps (scale 1:62500). Additional detail on the techniques employed in this study may be found in Bilby and Ward (1989).

We defined LWD as any piece of wood larger than 10 cm in diameter and 2 m long. Organic material not qualifying as LWD by this definition was considered fine organic debris.

All pieces of LWD within the bankfull channel of the surveyed stream reaches were measured with the exception of those pieces which were either floating free in the channel or resting in an unstable position atop a LWD accumulation. These pieces were considered to have a minimal impact on the channel form or stream function and thus were omitted. However, these pieces were rare and nearly all pieces meeting our size criteria were included in the survey.

We attempted to measure at least 50 pieces of wood at each study site. However, LWD was rare at some of the sites and riparian stand conditions changed before 50 pieces were encountered. Due to our criterion of 50 pieces of LWD per site, the length of stream channel surveyed varied with changing LWD abundance, ranging from less than 100 m to nearly 1.5 km.

Characteristics of the LWD pieces which were measured included diameter, taken at the center of the piece, length in and out of the channel, and the species of tree that produced the piece. Advanced decay prevented identification of species for about 10% of the surveyed pieces. Channel characteristics associated with LWD which were measured included surface area of pools, surface area of sediment accumulations, height of waterfalls, and volume of fine organic debris (organic material less than 10 cm in diameter and 2 m in length, including twigs, leaves, needles, etc.).

Average size of LWD pieces was compared between sites with a debris volume index (Bilby and Ward 1989). This variable was calculated by determining the geometric mean diameter and geometric mean total length (both in and outside the channel) for debris pieces in each surveyed reach. Frequency distributions of LWD diameters and lengths were skewed heavily towards smaller size classes; thus, a geometric mean was used to calculate average values for these variables (Bilby and Ward 1989). The debris volume index is the volume of a cyl-

Can. J. Fish. Aquat. Sci. Downloaded from www.nrcresearchpress.com by University of British Columbia on 01/24/13
For personal use only.

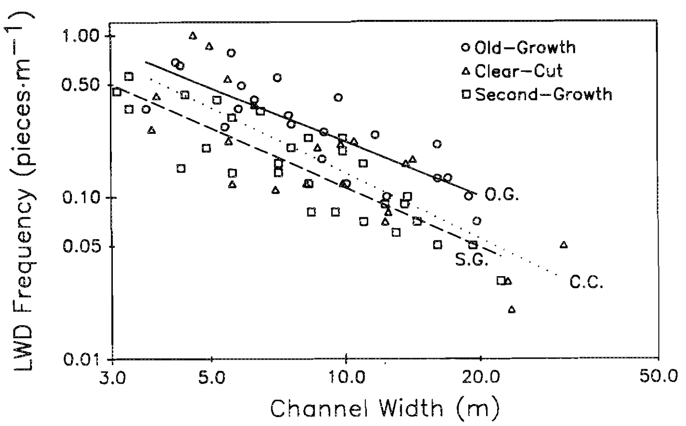

FIG. 1. Relationship between numbers of pieces of LWD per length of surveyed channel and channel width for the three stand-age classes (O.G. = old-growth, C.C. = clear-cut, S.G. = second-growth). There are significant differences among the slope values (ANOVA; $p < 0.05$). Equations for the regressions are as follows: old-growth, $\log_{10}$ LWD frequency $= -1.12 \log_{10}$ channel width $+ 0.46$ ($r^2 = 0.69$); clear-cut, $\log_{10}$ LWD frequency $= 1.35 \log_{10}$ channel width $+ 0.50$ ($r^2 = 0.66$); second-growth, $\log_{10}$ LWD frequency $= -1.23 \log_{10}$ channel width $+ 0.28$ ($r^2 = 0.75$).

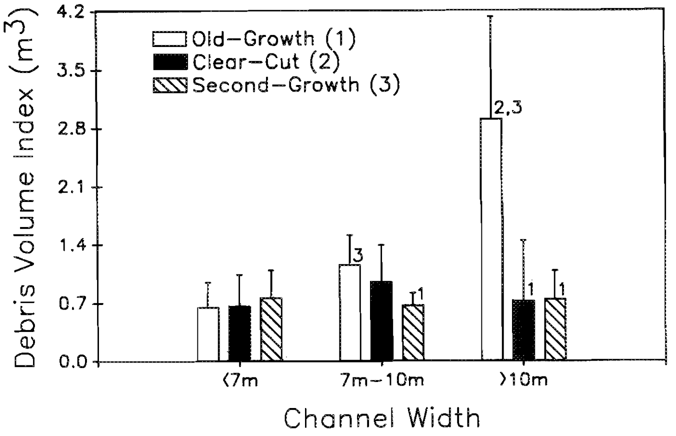

FIG. 2. Comparison of debris volume index (see text for definition) between stand-age classes for channels <7, 7–10, and >10 m wide. Numbers above the bars indicate significant differences from other stand-age classes (t-test; $p < 0.05$).

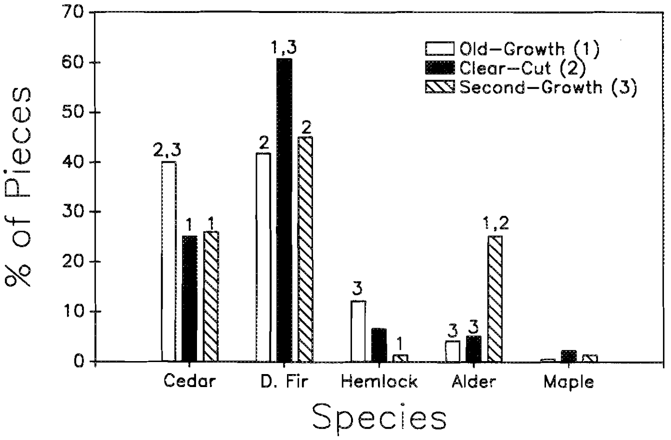

FIG. 3. Species distribution of pieces of LWD in the three stand-age classes. Values significantly different (t-test; $p < 0.05$) from corresponding values for different stand-age classes are denoted with a number above the bar. Cedar = western redcedar (*Thuja plicata*), D. Fir = Douglas fir (*Pseudotsuga menziesii*), Hemlock = western hemlock (*Tsuga heterophylla*), Alder = red alder (*Alnus rubra*), Maple = bigleaf maple (*Acer macrophyllum*).

inder with dimensions equal to the geometric mean diameter and length for each reach.

LWD-associated pools were assigned to one of four classes based on their morphology and method of formation (Bisson et al. 1982). The four classes we recognized were scour pools, plunge pools, backwater pools, and dammed pools.

The influence of fine organic debris on LWD function was examined by comparing the proportion of pieces of LWD retaining large amounts of fine debris ($\geqslant 0.5$ m^3) associated with pools, waterfalls, and sediment accumulations with the proportion of pieces of LWD retaining lesser amounts of fine debris associated with these channel features. The same comparison was made between the different pool types to determine if the presence of fine debris favored the formation of certain kinds of pools.

The amount, characteristics, and function of LWD change with changing stream size (Bilby and Ward 1989). Thus, stream size had to be considered in comparing LWD features and function between the three stand-age classes. Because of the variation in precipitation between the study sites, channel width, rather than watershed area, was used as an index of relative stream size.

Regression of LWD features or function against channel width was used for some of the analyses in this study. In cases where regression techniques were not used, streams were segregated into three channel-width classes: <7 m, 7–10 m, and >7 m. There were about an equal number of sites in each stream-size class for each stand-age class. Statistical comparisons of percentage values between stand-age classes and stream-size classes were made using a t-test for equality of two percentages (Sokal and Rohlf 1969).

Results

Abundance, Size, and Species

LWD abundance decreased with increasing stream size for all three stand-age classes (Fig. 1). However, old-growth sites had more wood than similarly sized streams at second-growth or clear-cut sites (t-test; $p < 0.05$). The frequency of LWD pieces in clear-cut and second-growth sites was 59 and 50%, respectively, of that measured in old-growth sites for streams at 15 m wide. In channels 5 m wide, LWD frequency in clear-cut and second-growth sites was 77 and 56%, respectively, of that seen at old-growth sites.

Debris volume index increased with increasing stream size at the old-growth sites (Fig. 2). However, no relationship between piece size and stream size was observed for clear-cut or second-growth sites. The debris volume index for old-growth sites was about four times greater than the other two stand-age classes for streams >10 m wide (ANOVA; $p < 0.05$). LWD piece size was also significantly greater at old-growth sites than at second-growth sites in channels 7–10 m wide. No statistical differences in piece size were observed between stand-age classes for streams <7 m wide.

There were significant differences between stand-age classes in the species distribution of the LWD (Fig. 3; t-test; $p < 0.05$).

Can. J. Fish. Aquat. Sci. Downloaded from www.nrcresearchpress.com by University of British Columbia on 01/24/13
For personal use only.

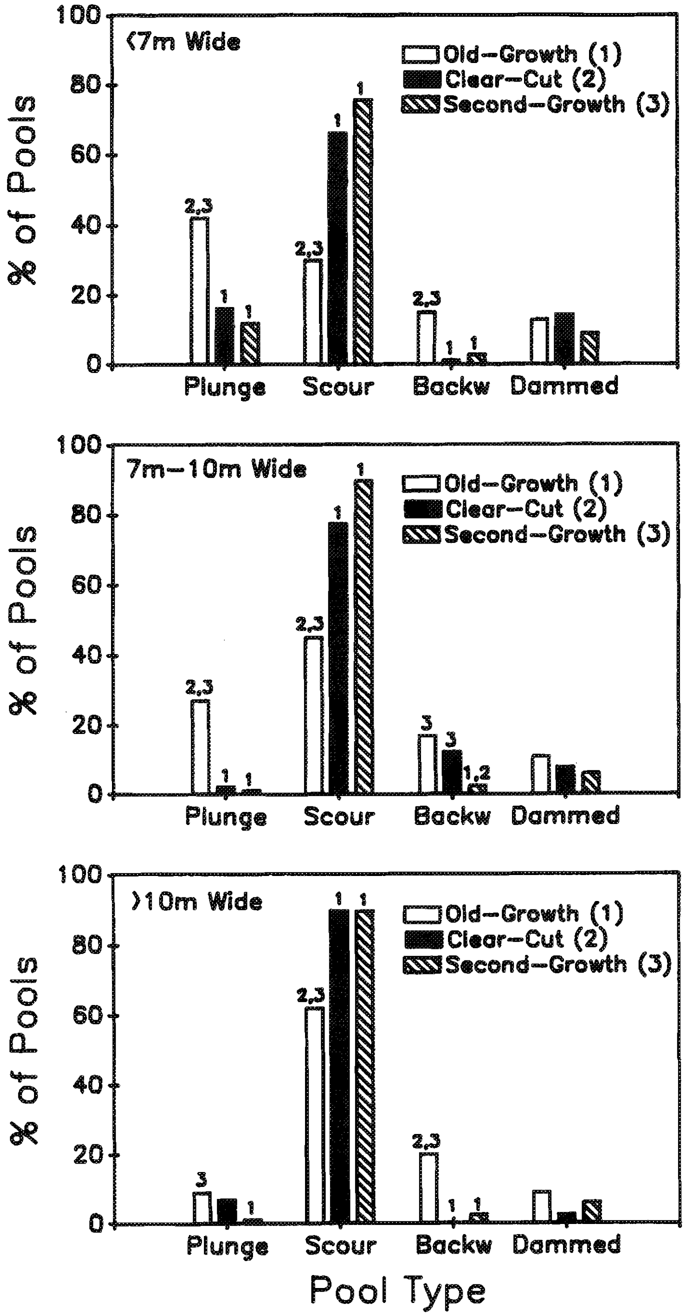

FIG. 4. Distribution of pool types for the three stand-age classes in each of the channel-width classes. Values significantly different (t-test; $p < 0.05$) from corresponding values for other stand-age classes are denoted with a number above the bar.

Western redcedar accounted for 40% of the debris pieces in the old-growth systems but contributed significantly lower proportions of LWD to clear-cut and second-growth sites. Douglas fir, the most commonly encountered species in all stand-age classes, contributed significantly more pieces of LWD in clear-cut systems than in the other two stand-age classes. The proportion of western hemlock was relatively low and progressively decreased from old-growth to clear-cut to second-growth sites. Red alder contributed significantly more pieces of LWD to second-growth sites than to old-growth or clear-cut sites. No differences were observed by stand-age class in the proportion of LWD contributed by bigleaf maple. However, this species did not produce more than 5% of the wood in any of the stand-age classes.

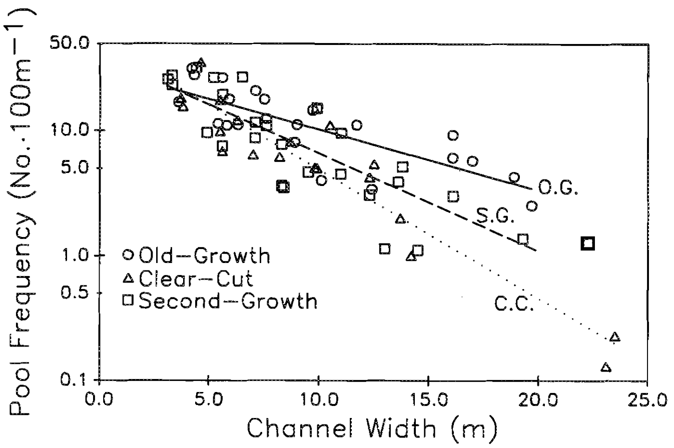

FIG. 5. Relationship between channel width and frequency of LWD-associated pools for the three stand-age classes (O.G. = old-growth, C.C. = clear-cut, S.G. = second-growth). There are significant differences among the slope values (ANOVA; $p < 0.05$). Regression equations are as follows: old-growth, $\log_{10}$ pool frequency = -0.05 channel width + 1.49 ($r^2 = 0.64$); clear-cut, $\log_{10}$ pool frequency = -0.10 channel width + 1.71 ($r^2 = 0.90$); second-growth, $\log_{10}$ pool frequency = -0.08 channel width + 1.59 ($r^2 = 0.70$).

Pools

The frequency of occurrence of different types of pools associated with LWD changed with stand-age class and stream size (Fig. 4). Pool types were the most diverse in streams bordered by old-growth forest. In these systems, scour pools increased and plunge pools decreased in abundance with increasing stream size (t-test; $p < 0.05$). Scour pools occurred significantly more frequently in clear-cut and second-growth systems than at old-growth sites for all three stream-size classes and were the predominant pool type in all stream-size classes at clear-cut and second-growth sites. Plunge pools formed by LWD were significantly more common at old-growth sites than at second-growth sites for all stream-size classes and at clear-cut sites in streams <7 m wide.

Backwater and dammed pools formed by LWD occurred less frequently than other pool types in all stand-age classes (Fig. 4). Backwater pools were more common at old-growth sites than at second-growth sites for all stream-size classes and at clear-cut sites for streams <7 m wide and >10 m wide (t-test; $p < 0.05$).

Frequency of LWD-associated pools decreased with increasing stream size for all three stand-age classes (Fig. 5) but was significantly greater at old-growth sites than at the other two stand-age classes (t-test; $p < 0.05$). Pool frequency was most similar among stand-age classes in smaller streams. Differences increased with increasing stream size, and frequency of pools associated with LWD in old-growth sites was more than twice that of second-growth sites and three times that of clear-cut sites for streams 15 m wide.

Surface area of debris-associated pools was not significantly different among the stand-age classes for streams <7 m wide or 7–10 m wide (Fig. 6). However, average pool surface area was significantly greater in streams >10 m wide at old-growth sites (t-test; $p < 0.05$), averaging more than twice the area of pools in clear-cut and second-growth systems.

Can. J. Fish. Aquat. Sci. Downloaded from www.nrcresearchpress.com by University of British Columbia on 01/24/13
For personal use only.

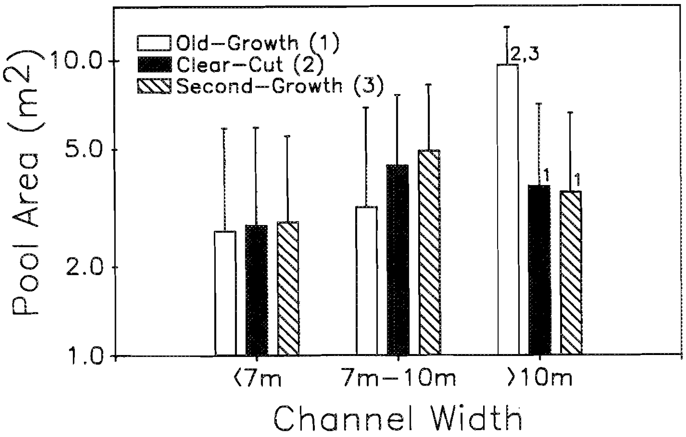

FIG. 6. Comparison of average surface area of scour pools between stand-age classes for different channel widths. Error bars indicate standard deviation. Values significantly different (*t*-test; $p < 0.05$) from corresponding values in other stand-age classes are denoted with a number above the bar.

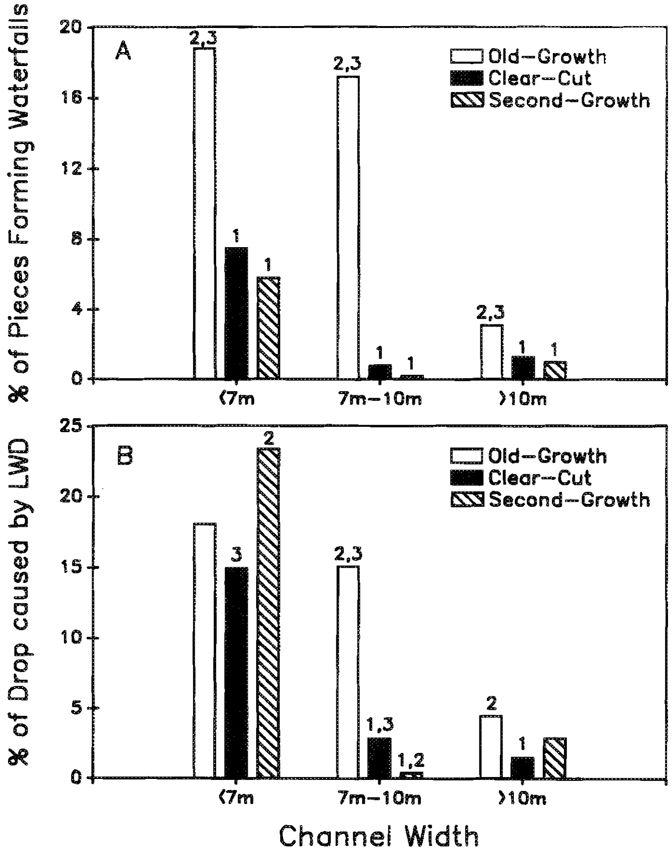

FIG. 7. (A) Proportion of pieces of LWD forming waterfalls and (B) proportion of the total drop in elevation of the surveyed stream sections accounted for by the summed height of LWD-formed waterfalls for the three age classes for each channel-width class. Values significantly different (*t*-test; $p < 0.05$) from corresponding values in other stand-age classes are denoted with a number above the bar.

Waterfalls

The proportion of pieces of LWD forming waterfalls was significantly greater at old-growth sites than at the other two stand-age classes for all stream-size classes (Fig. 7A; *t*-test; $p < 0.05$). The proportion of pieces forming waterfalls was greater in streams <7 m wide than in larger systems for all three stand-age classes (*t*-test; $p < 0.05$).

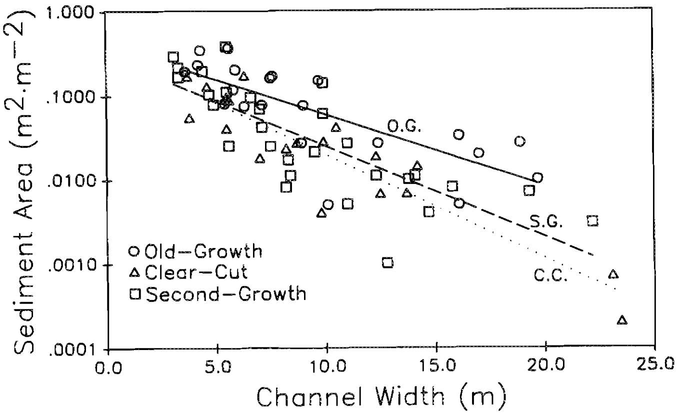

FIG. 8. Relationship between channel width and the surface area of the streambed occupied by LWD-associated sediment accumulations for the three stand-age classes (O.G. = old-growth, C.C. = clear-cut, S.G. = second-growth). There are significant differences among the intercept values (ANOVA; $p < 0.05$). Regression equations are as follows: old-growth, $\log_{10}$ sediment area = −0.08 channel width − 0.38 ($r^2 = 0.53$); clear-cut, $\log_{10}$ sediment area = −0.12 channel width − 0.47 ($r^2 = 0.84$); second-growth, $\log_{10}$ sediment area = −0.11 channel width − 0.53 ($r^2 = 0.62$).

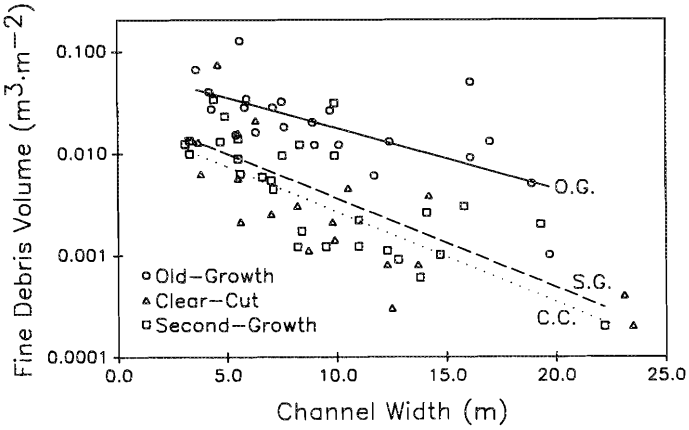

FIG. 9. Relationship between channel width and volume of fine debris associated with LWD for the three stand-age classes (O.G. = old-growth, C.C. = clear-cut, S.G. = second-growth). There are significant differences among the intercept values (ANOVA; $p < 0.05$). Regression equations are as follows: old-growth, $\log_{10}$ sediment volume = −0.06 channel width −1.16 ($r^2 = 0.48$); clear-cut, $\log_{10}$ volume = −0.09 channel width −1.70 ($r^2 = 0.59$); second-growth, $\log_{10}$ volume = −0.09 channel width −1.57 ($r^2 = 0.57$).

The proportion of the drop in elevation of a stream reach accounted for by summing the heights of waterfalls formed by LWD decreased with increasing stream size (Fig. 7B). Old-growth sites displayed a greater cumulative elevation drop caused by LWD than the other stand-age classes in streams 7–10 m wide and greater than the clear-cut sites in channels >10 m wide (*t*-test; $p < 0.05$).

Sediment

Proportion of the streambed covered by sediment stored by LWD decreased with increasing stream size for all three stand-

Can. J. Fish. Aquat. Sci. Downloaded from www.nrcresearchpress.com by University of British Columbia on 01/24/13
For personal use only.

TABLE 1. Proportion of pieces of LWD retaining <0.5 and $\geqslant 0.5$ m^3 of fine debris associated with pools. Values are significantly different for all stand-age classes (t-test; $p < 0.05$).

	Pieces of LWD retaining <0.5 m^3		Pieces of LWD retaining $\geqslant 0.5$ m^3	
	% forming pools	N	% forming pools	N
Old-growth	21	881	60	221
Clear-cut	28	858	82	51
Second-growth	39	1346	89	95

age classes (Fig. 8). Area of LWD-associated sediment was greater at old-growth sites than at the other two stand-age classes for all stream sizes (t-test; $p < 0.05$). Differences in this variable among the stand-age classes increased with stream size, with an estimated 16, 8, and 9% of the bed surface covered with LWD-associated sediment in channels 5 m wide at old-growth, clear-cut, and second-growth sites, respectively, compared with 2.5, 0.5, and 0.7% in channels 15 m wide.

Fine Organic Debris

The volume of fine organic debris per square metre of channel surface area decreased with increasing stream size for all stand-age classes (Fig. 9), but more fine debris was retained by LWD at old-growth sites than at the other two stand-age classes (t-test; $p < 0.05$). Volume of fine organic debris stored by LWD in channels 5 m wide was estimated at 0.035, 0.007, and 0.010 $m^3 \cdot m^{-2}$ at old-growth, clear-cut, and second-growth sites, respectively. The corresponding values for a 15-m-wide channels were 0.0087, 0.0010, and 0.0013 $m^2 \cdot m^{-3}$, respectively.

Fine Organic Debris and LWD Function

Differences between stand-age classes in the frequency of debris-associated pools (Fig. 5) were partly due to a greater amount of fine debris at old-growth sites, although the relative abundance of LWD also was an important factor. In all stand-age classes, pools were associated with pieces of LWD retaining $\geqslant 0.5$ m^3 of fine debris significantly more frequently than with LWD retaining <0.5 m^3 of fine debris (Table 1; t-test; $p < 0.05$). About 20% of the pieces of LWD at the old-growth sites had fine debris accumulations $\geqslant 0.5$ m^3 compared with 6% at clear-cut and 7% at second-growth sites.

The increased diversity of pool types observed at the old-growth sites may have been related to the large amount of fine organic debris at these sites (Table 2). Plunge and dammed pools were associated with accumulations of fine debris $\geqslant 0.5$ m^3 significantly more frequently than scour pools in all three stand-age classes (t-test; $p < 0.05$). Both plunge pools and dammed pools tend to be formed by obstructions that completely span the channel (Bilby and Ward 1989). Fine debris fills in the gaps in the framework provided by the LWD, resulting in more efficient blockage of stream flow. Since larger fine debris accumulations were rare at clear-cut and second-growth sites (Table 1), it is not surprising that plunge pools were rare and scour pools comprise the vast majority of pools in these systems.

Amount of fine organic debris associated with LWD also may have influenced the formation of depositional sites. LWD with fine debris accumulations $\geqslant 0.5$ m^3 retained sediment significantly more frequently than LWD pieces with less fine debris (Table 3; t-test; $p < 0.05$). Thus, accumulations of sediment associated with LWD were more frequent at old-growth sites due to both high levels of LWD and large amounts of fine debris.

TABLE 2. Proportion of the different pool types associated with fine debris accumulations $\geqslant 0.5$ m^3. Significant differences between pool types within a stand-age class are indicated with a letter (t-test; $p < 0.05$; s = scour pools, p = plunge pools, b = backwater pools, d = dammed pools).

	Pool type			
	Scour	Plunge	Backwater	Dammed
Old-growth				
$\geqslant 0.5$ m^3 (%)	36	49	33	56
Sign. diff.	p, d	s, b	p, d	s, b
N	131	88	58	41
Clear-cut				
$\geqslant 0.5$ m^3 (%)	8	37	33	35
Sign. diff.	p, b, d	s	s	s
N	216	27	12	31
Second-growth				
$\geqslant 0.5$ m^3 (%)	12	26	13	41
Sign. diff.	p, d	s	d	s, b
N	510	31	15	51

Discussion

Effect of Riparian Timber Harvest on LWD

Reduction in LWD amount and piece size as a result of timber harvest has generally been assumed to occur gradually due to a decrease in LWD input coupled with decomposition of material in the channel. However, our data indicate that many changes in LWD abundance, characteristics, and function occur during or shortly after timber harvest. During the 5-yr period separating our old-growth and clear-cut sites, wood amount decreased, average piece size in channels >10 m wide decreased, and the species mix of the LWD changed. It is unlikely that these changes could be attributed solely to decomposition of residual LWD and reduced LWD input over this short time period. The decrease in abundance of large, redcedar logs between the old-growth and clear-cut sites suggests that selective removal of this material from the channel during or shortly after logging may have been a factor in the reduction in LWD. Salvage of redcedar after timber harvest is a common practice in the Pacific Northwest. Removal of LWD from streams also has been shown to destabilize wood remaining in the channel (Bilby 1984), thus promoting flushing of wood downstream and contributing to the decrease in LWD amount. Selective removal of larger logs from channels may also be partly responsible for the lack of relationship between stream size and debris volume index at clear-cut sites. However, since no records of wood salvage from stream channels are kept, the extent to which this practice occurred on our study sites cannot be determined.

Changes in LWD characteristics from the clear-cut to second-growth conditions likely reflect decomposition of residual wood in the channel coupled with reduced input and a change in the composition of the riparian vegetation. The progressive decrease in western hemlock abundance with time after harvest

Can. J. Fish. Aquat. Sci. Downloaded from www.nrcresearchpress.com by University of British Columbia on 01/24/13
For personal use only.

TABLE 3. Proportion (%) of the pieces of LWD containing fine debris accumulations ≥0.5 and <0.5 m^3 associated with depositional sites. Pieces of wood with large fine debris accumulations are significantly more likely to be associated with areas of deposited sediment in all cases (t-test; $p < 0.05$).

	Channel width					
	<7 m		7–10 m		>10 m	
	≥0.5 m^3	<0.5 m^3	≥0.5 m^3	<0.5 m^3	≥0.5 m^3	<0.5 m^3
Old-growth	69.0	30.1	63.8	20.1	36.9	11.9
Clear-cut	60.0	19.7	66.7	16.5	46.2	17.2
Second-growth	64.7	36.9	57.5	20.9	58.1	18.3

indicates elimination of this species from the system without replacement. Since hemlock is less decay resistant than many other conifer species, reduction in its abundance should occur relatively rapidly. The increase in red alder debris in streams in second-growth sites is due to the abundance of this species at the second-growth sites.

There were very large differences between stand-age classes in the amount of fine debris stored by LWD, with old-growth sites containing more fine debris than the other two stand-age classes. Three factors contributed to the large amount of LWD-associated fine debris at the old-growth sites: abundant LWD to retain fine organic matter, a high rate of input from the terrestrial system (Gregory et al. 1987), and high proportions of debris from decay-resistant coniferous trees (Harmon et al. 1986). In contrast, the clear-cut sites have less LWD, very low contributions of organic matter from the terrestrial system, and a high proportion of material from deciduous trees or herbaceous vegetation, which decomposes rapidly. The second-growth sites have conditions intermediate to the two other stand-age classes, with little LWD and inputs of relatively easily decayed terrestrial debris (primarily red alder litter).

Differences between the three stand-age classes in certain characteristics and functions of LWD are accentuated in larger streams. Average piece size, pool frequency, and average pool area exhibit less difference in smaller streams than in larger systems. Differences by stand-age class in the amount of sediment accumulated by LWD or amount of fine organic matter associated with wood are less affected by stream size. In general, however, changes in LWD features and function after timber harvest of streamside vegetation tend to be most pronounced in larger streams.

Changes in LWD over Time

Models of changes in LWD abundance following removal of riparian trees have assumed a relatively slow decline caused by decomposition of residual in-channel wood. Swanson and Lienkaemper (1978) hypothesized that relatively little change in pre-harvest levels of LWD in Pacific Northwest streams would occur for 50 yr due to slow decomposition of pre-harvest LWD. A model by Grette (1985) proposed a linear decline in LWD amount with time, at a rate of slightly less than 1%·yr^{-1}. Input of LWD from the deciduous riparian vegetation resumes approximately 40 yr after harvest, but is insufficient to offset decomposition, leading to LWD amounts 50 yr after harvest of approximately 75% of the old-growth level. Murphy and Koski (1989) suggested a faster rate of decline for southeastern Alaska streams, with larger pieces of LWD being eliminated at the rate of 1–3%·yr^{-1}, depending on characteristics of the channel.

None of these models, however, accurately predicted the patterns of change in LWD abundance reported here. Using the regressions developed from our data for LWD frequency (Fig. 1) and average debris volume index (Fig. 2), we estimated wood volume in streams 5, 10, and 15 m wide for each stand-age class (Fig. 10A). The regressions in Fig. 5, 8, and 9 were used to calculate pool frequency, area of sediment accumulations, and volume of fine organic material (Fig. 10B, 10C, 10D). Three channel widths were examined, since mean LWD piece size is influenced by stream size (Bilby and Ward 1989) and, as a result, has an influence on input and elimination rate (Likens and Bilby 1982; Murphy and Koski 1989). We have assumed that our clear-cut sites were all 5 yr post-harvest and the second-growth sites were all 50 yr post-harvest.

Total volume of LWD per 100 m of channel decreased 22% from old-growth levels 5 yr after harvest and 35% after 50 yr in streams 5 m wide (Fig. 10A). The magnitude of decrease became progressively greater with increasing channel width, with a depression in LWD volume of 47 and 86% in channels 10 and 15 m wide, respectively, 5 yr after harvest. The very large drop in volume in the larger streams is an indication of the decrease in both piece frequency and piece size. LWD volume decreased 71 and 94% from old-growth levels in channels 10 and 15 m wide, respectively, 50 yr after logging. The rate of decrease in LWD abundance between our old-growth and second-growth sites is comparable with that reported in other studies (Grette 1985; Murphy and Koski 1989). However, our data showed that the majority of this decrease occurred within the first 5 yr after harvest.

Pool frequency in channels 5 m wide is only slightly greater at old-growth sites than at clear-cut and second-growth sites (Fig. 10B). However, in 10- and 15-m-wide streams, pool frequency decreased by more than 50% in the 5 yr after harvest and then changed relatively little over the next 45 yr. Estimated decreases in sediment stored by LWD over time were greater than 50% for all three sized streams, with nearly all the change occurring shortly after timber harvest (Fig. 10C).

Fine debris volume decreases at a much greater relative rate than LWD following removal of the streamside vegetation (Fig. 10D). Fine debris was reduced by about 90% within 5 yr of harvest, regardless of stream size. Little change in the amount of stored fine debris occurred between 5 and 50 yr post-harvest.

Management of Riparian Areas

Pacific Northwest states and provinces have recently instituted regulations or guidelines requiring retention of standing trees along stream channels during timber harvest to provide a source of future LWD. In Washington, from 50 to 200 trees

Can. J. Fish. Aquat. Sci. Downloaded from www.nrcresearchpress.com by University of British Columbia on 01/24/13
For personal use only.

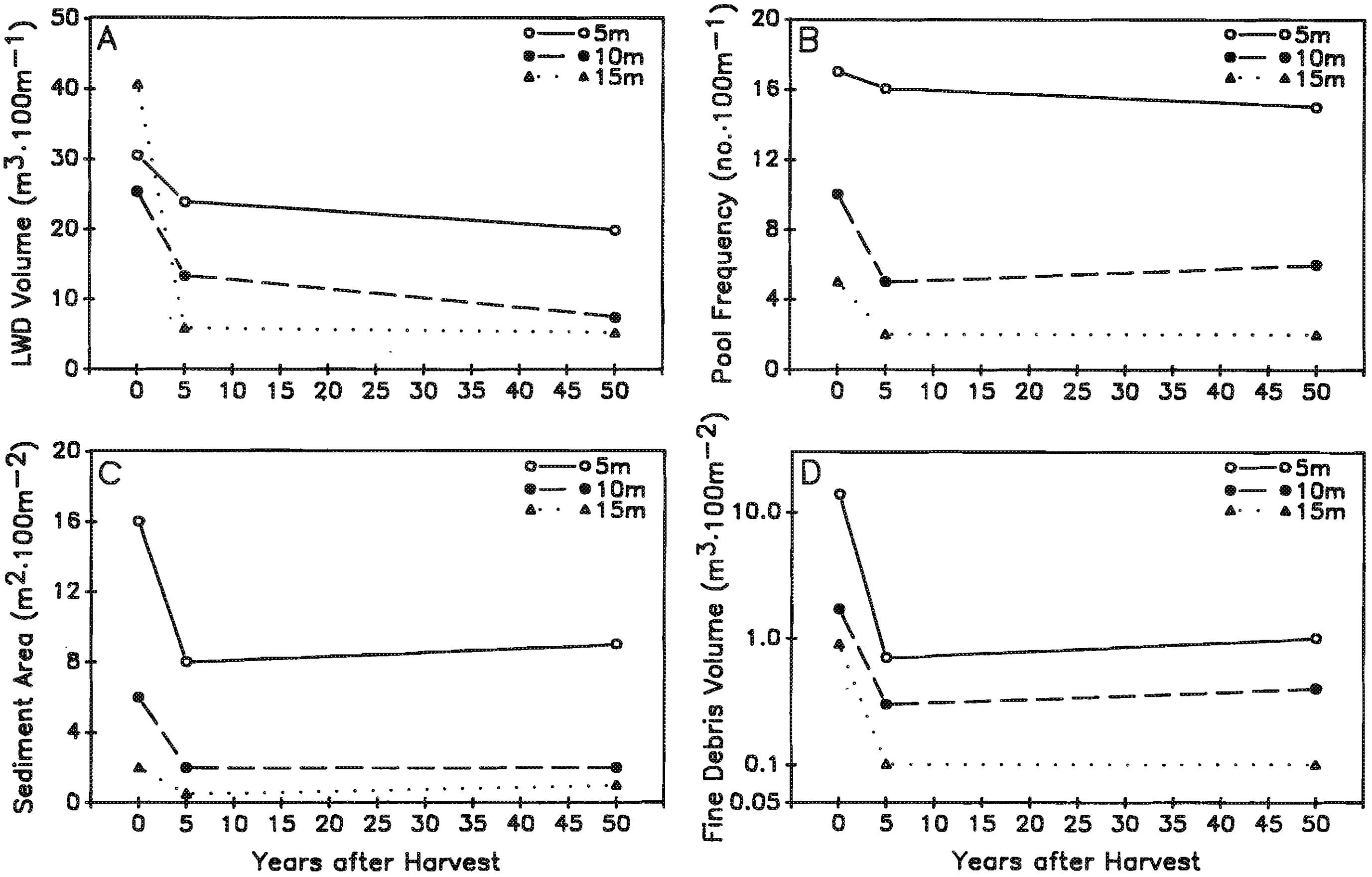

FIG. 10. Changes in LWD abundance and function with time after timber harvest for streams of three different widths. (A) Volume of LWD per length of channel; (B) pool frequency; (C) area of sediment accumulated by LWD; (D) volume of fine organic matter.

per 300 m of stream length must be retained after timber harvest, varying as a function of channel width (Bilby and Wasserman 1989). The width of the protected area also varies with stream size, ranging from 8 to 30 m on either side of the channel. Thus, the patterns of change in LWD abundance and function seen in this study resulted from timber harvest practices that are no longer in use. However, until the early 1980s, the trees along many streams were removed during timber harvest. The effect of this practice was the creation of riparian stands composed largely of red alder. Our data indicate that riparian zones with this type of vegetative composition (our second-growth sites) may not supply sufficient LWD, especially to larger streams. Also, the rapidly decomposing fine organic matter produced by deciduous vegetation is less effective at influencing channel structure than that from coniferous trees. Encouragement of conifer growth in riparian zones dominated by red alder may help alleviate some of these problems.

The vegetative and structural diversity of alder-dominated riparian stands may be increased by active management. Planting of conifer seedlings in riparian areas might be successful if the proper conditions for survival and growth can be created (Emmingham et al. 1989). Clearing small areas of riparian vegetation would be necessary in most cases to provide the conditions required by shade-intolerant conifer species, such as Douglas fir. Control of understory vegetation for several years could also be necessary. Release of suppressed conifers already present in the riparian area by removing the overstory is another possible option (Ferguson and Adams 1980).

The influence of fine organic debris on LWD function also suggests that vegetative characteristics of the riparian zone should be considered when selecting locations for stream habitat enhancement projects that include placement of wood. Our study indicates that LWD placement in streams would achieve improved results if conducted on a site receiving large inputs of fine coniferous debris.

Acknowledgments

We thank J. Heffner and W. Stonecypher for assistance with the field surveys. Helpful comments on the manuscript were provided by P. Bisson, J. Rochelle, K. Sullivan, D. Mumper, D. Wilbur, and two anonymous reviewers.

References

BENKE, A. C., T. C. VAN ARSDALL, D. M. GILLESPIE, AND F. K. PARRISH. 1984. Invertebrate productivity in a subtropical blackwater river: the importance of habitat and life history. Ecol. Monogr. 54: 25–63.

BESCHTA, R. L. 1979. Debris removal and its effects on sedimentation in an Oregon Coast Range stream. Northwest Sci. 53: 71–77.

BILBY, R. E. 1979. The function and distribution of organic debris dams in forest stream ecosystems. Ph.D. thesis, Cornell University, Ithaca, NY. 143 p.

1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. Ecology 62: 1234–1243.

1984. Post-logging removal of woody debris affects stream channel stability. J. For. 82: 609–613.

Can. J. Fish. Aquat. Sci. Downloaded from www.nrcresearchpress.com by University of British Columbia on 01/24/13
For personal use only.

BILBY, R. E., AND G. E. LIKENS. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61: 1107–1113.

BILBY, R. E., AND J. W. WARD. 1989. Changes in the characteristics and function of woody debris with increasing size of streams in western Washington. Trans. Am. Fish. Soc. 118: 368–378.

BILBY, R. E., AND L. J. WASSERMAN. 1989. Forest practices and riparian management in Washington state: data based regulation development, p. 87–94. *In* R. E. Gresswell, B. A. Barton, and J. L. Kershner [ed.] Practical approaches to riparian resource management. U.S. Department of the Interior, Bureau of Land Management, Billings, MT.

BISSON, P. A., J. L. NIELSEN, R. A., PALMASSON, AND L. E. GROVE. 1982. A system of naming habitat types in small streams with examples of habitat utilization by salmonids during low streamflow, p. 62–73. *In* N. B. Armantrout [ed.] Acquisition and utilization of aquatic habitat inventory information. American Fisheries Society, Bethesda, MD.

BISSON, P. A., ET AL. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present and future, p. 143–190. *In* E. O. Salo and T. Cundy [ed.] Proceedings of an interdisciplinary symposium on streamside management: forestry and fisheries interactions. University of Washington Press, Seattle, WA.

BUSTARD, D. R., AND D. W. NARVER. 1975. Aspects of the winter ecology of juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). J. Fish. Res. Board Can. 32: 667–680.

DOLLOFF, C. A. 1986. Effects of stream cleaning on juvenile coho salmon and Dolly Varden in southeast Alaska. Trans. Am. Fish. Soc. 115: 743–755.

ELLIOTT, S. T. 1986. Reduction of a Dolly Varden population and macrobenthos after removal of logging debris. Trans. Am. Fish. Soc. 115: 392–400.

EMMINGHAM, W. H., M. BONDI, AND D. E. HIBBS. 1989. Underplanting western hemlock in an alder thinning: early survival, growth, and damage. New For. 3: 31–43.

FERGUSON, D. E., AND D. L. ADAMS. 1980. Response of advanced grand fir regeneration to overstory removal in northern Idaho. For. Sci. 26: 537–545.

GREGORY, S. V., ET AL. 1987. Influence of forest practices on aquatic production, p. 233–255. *In* E. O. Salo and T. Cundy [ed.] Proceedings of an interdisciplinary symposium on streamside management: forestry and fisheries interactions. University of Washington Press, Seattle, WA.

GRETTE, G. B. 1985. The role of large organic debris in juvenile salmonid rearing habitat in small streams. Master's thesis, University of Washington, Seattle, WA. 105 p.

HARMON, M. E., ET AL. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15: 133–302.

HEEDE, B. H. 1972. Influences of a forest on the hydraulic geometry of two mountain streams. Water Resour. Bull. 8: 523–530.

HUNTTING, M. T., W. A. BENNETT, V. A. LIVINGSTON, AND W. S. MOEN. 1961. Geologic map of Washington. Washington Department of Mines and Geology, Olympia, WA.

LIENKAEMPER, G. W., AND F. J. SWANSON. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. Can. J. For. Res. 17: 150–156.

LIKENS, G. E., AND R. E. BILBY. 1982. Development, maintenance, and role of organic debris dams in New England streams, p. 122–128. *In* F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanston [ed.] Sediment budgets and routing in forested drainage basins. U.S. For. Serv. Res. Pap. PNW-141.

LISLE, T. E. 1986. Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California. Geol. Soc. Am. Bull. 8: 999–1011.

LISLE, T. E., AND H. M. KELSEY. 1982. Effects of large roughness elements on the thalweg course and pool spacing, p. 134–135. *In* L. B. Leopold [ed.] American geomorphological field group field trip guidebook, 1982 conference, Pinedale, Wyoming. American Geophysical Union, Berkeley, CA.

LONG, B. A. 1987. Recruitment and abundance of large woody debris in an Oregon coastal stream. Master's thesis, Oregon State University, Corvallis, OR. 65 p.

MCMAHON, T. E., AND G. F. HARTMAN. 1989. Influence of cover complexity and current velocity on winter habitat use by juvenile coho salmon (*Oncorhynchus kisutch*). Can. J. Fish. Aquat. Sci. 46: 1551–1557.

MEGAHAN, W. F. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho Batholith, p. 114–121. *In* F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanston [ed.] Sediment budgets and routing in forested drainage basins. U.S. For. Serv. Res. Pap. PNW-141.

MURPHY, M. L., AND K. V. KOSKI. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. N. Am. J. Fish. Manage. 9: 427–436.

NAIMAN, R. J., AND J. R. SEDELL. 1979. Relationships between metabolic parameters and stream order in Oregon. Can. J. Fish. Aquat. Sci. 37: 834–847.

ROBISON, E. G., AND R. L. BESCHTA. 1990. Characteristics of coarse woody debris for several coastal streams of southeast Alaska, USA. Can. J. Fish. Aquat. Sci. 47: 1684–1693.

SEDELL, J. R., AND K. J. LUCHESSA. 1982. Using the historical record as an aid to salmonid habitat enhancement, p. 210–223. *In* N. B. Armantrout [ed.] Acquisition and utilization of aquatic habitat inventory information. American Fisheries Society, Bethesda, MD.

SOKAL, R. R., AND F. J. ROHLF. 1969. Biometry. W. H. Freeman and Co., San Francisco, CA. 776 p.

STERNES, G. L. 1969. Climatological handbook: Columbia basin states precipitation. Vol. 2. Pacific Northwest River Basins Commission, Meteorology Committee, Vancouver, WA.

SWANSON, F. J., AND G. W. LIENKAEMPER. 1978. Physical consequences of large organic debris in Pacific Northwest Streams. U.S. For. Serv. Gen. Tech. Rep. PNW-69.

SWANSON, F. J., G. W. LIENKAEMPER, AND J. R. SEDELL. 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. U.S. For. Serv. Gen. Tech. Rep. PNW-56.

TSCHAPLINSKI, P. J., AND G. F. HARTMAN. 1983. Winter distribution of juvenile coho salmon (*Oncorhynchus kisutch*) before and after logging in Carnation Creek, British Columbia, and some implications for overwinter survival. Can. J. Fish. Aquat. Sci. 40: 452–461.

WENDLER, H. O., AND G. DESCHAMPS. 1955. Logging dams on coastal Washington streams. Wash. Dep. Fish. Fish. Res. Pap. 1: 1–12.

Appendix

TABLE A.1. Characteristics of the surveyed stream sections and the number of pieces of LWD measured at each site (o.g. = old-growth, c.c. = clear-cut, s.g. = second-growth).

Stream	Stand condition	Channel width (m)	Basin area (km^2)	Pieces measured (*N*)
Deschutes River Basin				
Hard Cr.	o.g.	5.6	1.7	60
Unnamed stream	o.g.	5.8	1.0	50
Mine Cr.	o.g.	7.5	2.7	50
Thorn Cr.	o.g.	7.6	3.6	52
West Fork Cr.	o.g.	9.0	8.7	51
Lewis Cr.	c.c.	3.8	3.0	50
Hard Cr.	c.c.	5.5	2.2	50
Upper Deschutes R.	c.c.	5.5	2.6	50
Little Deschutes R.	c.c.	5.6	3.9	50
Deschutes R.	c.c.	8.7	12.7	50
Thurston Cr.	s.g.	4.9	9.6	50
Mitchell Cr.	s.g.	8.3	21.9	50
North River Basin				
Fall R.	o.g.	12.4	30.4	50
Fall R.	c.c.	8.2	24.2	51
Unnamed stream	o.g.	3.6	2.1	50
Skookumchuck River Basin				
Unnamed stream	o.g.	4.2	0.8	50
Unnamed stream	o.g.	4.3	0.4	53
Unnamed stream	o.g.	5.4	2.3	50
Deer Cr.	o.g.	6.3	2.9	51
U. Skookumchuck R.	o.g.	7.1	1.7	50
L. Skookumchuck R.	o.g.	17.0	26.6	50
Unnamed stream	c.c.	4.6	1.3	50
Big Water Cr.	c.c.	6.3	5.2	60
Skookumchuck R.	c.c.	10.5	15.9	50
Upper Hanaford Cr.	s.g.	3.3	3.5	50
Laramie Cr.	s.g.	4.3	7.8	50
Three Deer Cr.	s.g.	4.4	4.5	51
Lower Hanaford cr.	s.g.	9.9	33.8	51
U. Skookumchuck R.	s.g.	11.0	60.6	50
L. Skookumchuck R.	s.g.	13.0	72.1	50

TABLE A.1. (*Continued*)

Stream	Stand condition	Channel width (m)	Basin area (km^2)	Pieces measured (N)
Abernathy Creek Basin				
Abernathy Cr.	s.g.	11.0	31.2	50
Newaukum River Basin				
Newaukum R.	o.g.	8.9	18.1	53
N.F. Newaukum R.	c.c.	7.0	19.0	50
Hemlock Hole Cr.	s.g.	5.6	9.1	50
N.F. Newaukum R.	s.g.	13.6	18.9	50
S.F. Newaukum R.	s.g.	13.8	60.6	50
Kalama River Basin				
Arnold Cr.	c.c.	3.7	2.6	50
Gobar Cr.	c.c.	12.3	54.3	48
Nisqually River Basin				
Hiawatha Cr.	c.c.	9.8	12.3	50
Little Nisqually R.	c.c.	13.7	21.9	50
Beaver Cr.	s.g.	7.6	29.0	50
Busy Wild Cr.	s.g.	12.3	41.9	50
Upper Mashel R.	s.g.	14.5	48.7	50
Middle Mashel R.	s.g.	19.3	96.3	47
Lower Mashel R.	s.g.	22.3	136.8	36
Coweeman River Basin				
Baird Cr.	s.g.	8.3	19.9	50
Lewis River Basin				
Upper Canyon Cr.	o.g.	10.1	12.7	50
Middle Canyon Cr.	o.g.	16.1	33.0	50
Fly Cr.	o.g.	18.9	50.3	46
Lower Canyon Cr.	o.g.	19.7	68.0	50
Canyon Cr.	c.c.	23.5	74.6	19

TABLE A.1. (*Concluded*)

Stream	Stand condition	Channel width (m)	Basin area (km^2)	Pieces measured (N)
Upper Chehalis River Basin				
Salmon Cr.	c.c.	9.9	55.4	50
Upper Chehalis R.	c.c.	12.5	29.6	51
Unnamed stream	s.g.	3.1	2.0	50
Capps Cr.	s.g.	3.3	2.6	50
Big Cr.	s.g.	5.6	9.3	50
S.F. Stillman Cr.	s.g.	9.5	23.1	50
S.F. Chehalis R.	s.g.	16.1	43.7	50
Willapa River Basin				
Trap Cr.	s.g.	9.9	23.3	50
Grays River Basin				
E.F. Grays R.	o.g.	11.7	7.5	49
N.F. Grays R.	o.g.	16.1	21.9	50
Toutle River Basin				
Eighteen Cr.	s.g.	5.2	5.9	50
Thirteen Cr.	s.g.	6.5	7.9	50
Devils Cr.	s.g.	7.1	16.1	50
Upper Hemlock Cr.	s.g.	7.1	13.5	50
Lower Hemlock Cr.	s.g.	8.4	30.6	50
Tilton River Basin				
M.F. Tilton R.	o.g.	5.9	1.3	50
Otter Cr.	o.g.	9.7	3.8	51
Wallanding Cr.	c.c.	14.2	20.5	50
N.F. Tilton R.	c.c.	23.1	83.7	30

Can. J. Fish. Aquat. Sci. Downloaded from www.nrcresearchpress.com by University of British Columbia on 01/24/13
For personal use only.