A review of empirical source distance data for the recruitment of large woody debris to forested streams

by

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Abstract

We have assembled published or Internet-accessible unpublished measurements of cumulative inputs of large woody debris (LWD) to stream channels as a function of lateral distance from the stream channel (i.e., “LWD source distance curves”) in order to examine relationships between source distances and stream characteristics that are expected to be associated with dominant input processes. We obtained 137 source distance curves from 13 separate studies, most from coniferous forests along the Pacific coast of the U.S.A. From each LWD source distance curve, we determined graphically the distances to provide specified proportions of the cumulative LWD input (i.e., the distance for 50%, 75%, 80%, 90%, or 95% of the cumulative number or volume of LWD pieces at a reach). We used these data to examine the effects of input process (bank erosion, tree fall, land slides), stream channel type (riffle-pool, cascade-pool, step-pool), stream width, and riparian vegetation height on the source distances at which specific proportions (usually 90%) of the cumulative LWD inputs were attained. Few data sets provided complete coverage of the suite of variables that we wished to examine, so different analyses are based on different subsets of the data.

LWD source distance curves were variable within geographical areas with similar vegetation types and topography. Some of this variation is attributable to site characteristics which influence the mechanisms through which LWD enters the channel. Source distances which accounted for 90% of the cumulative numbers or volumes of LWD pieces increased with increasing tree height. The source distance which supplied 90% of the cumulative volume of LWD inputs differed among LWD delivery processes, being greater where tree fall was identified as the dominant input process than for bank erosion and land slides. Channel type and size influenced source distances for volume inputs, but the effect of channel type varied with channel width. Volume source distances at riffle-pool channels varied little with channel width, but source distances generally increased with channel size at cascade-pool and step-pool channels. We provide quantile plots of the distribution of lateral distances within which specified proportions of cumulative LWD inputs originated, which allow managers to determine riparian buffer widths that will attain specific management objectives for LWD recruitment with a specified probability.

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Introduction

Riparian forests supply wood to adjacent stream channels (McDade et al. 1990, Benda et al. 2002). Such riparian-derived wood may interact with stream flow to alter the hydraulics, sediment dynamics, geomorphology (Keller and Swanson 1979, Gurnell et al. 2002), and biological productivity (Smock et al. 1989, Wallace et al. 1995) of the receiving stream reach. The fate and effects of riparian-derived wood subsequent to its entry to the stream are strongly influenced both by characteristics of the piece such as its diameter, length, orientation, density, and the presence of a rootwad and by those of the channel such as depth of flow, width, slope, surface roughness, and the presence of obstructions (Nakamura and Swanson 1994, Braudrick and Grant 2000, Haga et al. 2002, Bocchiola et al. 2006a). Wood whose dimensions are large relative to channel dimensions will tend to remain near its entry location (Hilderbrand et al. 1998) and may exert a significant influence on the physical processes that shape the channel. Smaller pieces of wood may remain temporarily near their entry points, but will be transported downstream during high discharge (Haga et al. 2002) unless they become incorporated into stable debris jams initiated by a large “key” piece of wood (Abbe and Montgomery 2003).

“Large” woody debris is often defined operationally by the minimum-sized piece that will induce geomorphic change. A stable piece of wood will locally modify the water surface profile (Bocchiola et al. 2006b) and flow velocities (Abbe and Montgomery 1996), altering patterns of energy dissipation at a site. In alluvial channels, the flow changes may induce scour adjacent or beneath the piece (Keller and Swanson 1979, Abbe and Montgomery 1996, Buffington et al. 2002) and sediment deposition in low velocity zones upstream (Megahan 1982, Montgomery et al. 1996) and/or downstream (Keller and Swanson 1979) of the piece. The pattern of scour and deposition induced by stable wood within an alluvial channel increases the frequency of pools (Montgomery et al. 1995) and the total area or volume comprised by pools (Bisson et al 1987, Buffington et al. 2002). Heterogeneity of sediment texture (Buffington and Montgomery 1999) and of channel gradient (Faustini and Jones 2003) also increases.

Large woody debris will also alter the biological productivity of a stream reach. The alterations to stream hydraulics induced by woody debris retard the downstream transport of water, solutes, and materials in suspension (Gurnell et al. 2002). Stable wood within stream channels traps particulate organic matter (Bilby and Likens 1980, Smock et al. 1989) and modifies the storage and release of nutrients (Bilby 1981, Valett et al. 2002), potentially to increase the production of benthic invertebrates (Wallace et al. 1995). Instream wood also increases the surface available as a substrate for heterotrophic and autotrophic micro-organisms (Sinsabaugh et al. 1991), serves directly as a carbon source for xylophagous organisms (Anderson et al. 1978, Collier et al. 2000), and produces fine particulate organic matter (Ward and Aumen 1986). It may also serve as protective overhead cover for fishes, independently of its geomorphic function (Shirvell 1990). In general, the diversification of habitats induced by stable wood within a stream channel improves conditions for stream-rearing salmonid fishes (House and Boehne 1986, Fausch and Northcote 1992, Roni and Quinn 2001). Maintaining normal quantities of wood in stream channels is therefore an important goal for the management of riparian areas.

Wood enters a stream reach from the adjacent riparian forest via several processes, including: bank erosion, overbank flooding, tree fall from natural mortality or windthrow, and landslides (Swanson and Lienkaemper 1978, Keller and Swanson 1979, Murphy and Koski 1989, Palik et al. 1998, Benda et al. 2002, Acker et al. 2003, Benda et al. 2003). It may also enter from upstream reaches by fluvial transport (Kreutzweiser et al. 2005) or by debris torrents (May and Gresswell 2003). Wood is removed from the channel by fluvial transport as pieces decay and/or fragment to a size that can be moved by prevailing flows. The quantity of wood found within a stream reach at any time thus will reflect a shifting balance between input and removal processes. Where inputs are greatly reduced for long periods, as when riparian vegetation is removed and the regenerating vegetation is still too small to produce stable wood, instream quantities of stable, "functional" wood will decline (Murphy and Koski 1989, Bilby and Ward 1991) and stream channels may evolve towards a simpler geomorphic structure (Bilby and Ward 1991) that may have a reduced ability to produce fish (Fausch and Northcote 1992) or fish-food organisms. Reduced wood supply from cleared riparian areas may persist for many decades (Murphy and Koski 1989).

To avoid these undesirable effects, many resource management agencies have adopted regulations intended to preserve riparian forest and maintain normal inputs of wood. Commonly the protective regulations take the form of mandatory, prescribed, undisturbed or minimally disturbed riparian setbacks ("buffers") adjacent to the stream channel (Lee et al. 2004). Because of the value of the merchantable timber left within riparian buffers, and in urban areas because of the value of the cleared land itself, the width of the riparian buffer that is necessary to maintain normal inputs of large woody debris to a stream has frequently been a contentious issue. In urban settings where, once cleared, riparian areas will remain un-treed, ensuring that sufficient riparian forest is retained in buffers to assure the adequate long-term provision of LWD is particularly important.

Factors that influence source distances for the delivery of functional large woody debris to streams

The lateral distance over which wood is delivered to a stream channel from the adjoining forest depends on characteristics of the vegetation and on the dominant delivery mechanisms operating at a site. Tree density, size, and mortality rate, and lateral zonation in these (e.g., transitions between true riparian and upland plant communities along soil-moisture gradients), will influence the quantity, piece size, and origin of wood entering the active stream channel. The physical process by which wood enters the channel influences the lateral distance from which it is recruited and the resulting piece size. The processes that commonly move wood directly from adjacent areas into the stream channel (bank erosion, tree fall or windthrow, landslides) operate over different lateral distances (Benda et al. 2002, May and Gresswell 2003). Bank erosion will only deliver trees at the current channel edge (Murphy and Koski 1989, Benda et al. 2002), although unconfined alluvial channels wider than about 15 m have sufficient stream power to migrate laterally across forested floodplains (Beechie et al. 2006) and so may obtain LWD over greater lateral distances than smaller riffle-pool channels. Severe flooding can recruit wood from the near channel portion of the active floodplain (Palik et al. 1996, Acker et al. 2003), but on unconstrained reaches much of the wood may actually be delivered through bank erosion. Dead fall will deliver LWD from distances up to about one tree height from the channel (Van Sickle and Gregory 1990). Similarly, windthrow will normally deliver wood only within one tree height of the channel (Grizzel et al. 2000, May and Gresswell 2003). Landslides may introduce wood from longer distances (Benda et al. 2002, May and Gresswell 2003, Reeves et al. 2003) if slopes are connected to the channel, but will normally occur only on steep sideslopes with low-cohesion overburden (Swanston and Howes 1991).

The relative importance of the different mechanisms by which wood is delivered to an adjacent stream channel varies with channel characteristics (Lienkaemper and Swanson 1987, Murphy and Koski 1989, Martin and Benda 2001, Reeves et al. 2003). The systematic changes in channel size, gradient, substrate, and hillslope coupling along drainage networks which define channel types reflect changes in the processes that deliver and transport sediments (Montgomery and Buffington 1997). LWD inputs respond to the same processes, e.g., Martin and Benda (2001) found that the recruitment of LWD from bank erosion increased systematically with drainage area in an Alaskan watershed. Differences in LWD input mechanisms among channel types can be thought of conceptually as systematic variation in rates of landslides and bank erosion along the drainage network, superimposed on a background rate of tree fall that is less strongly associated with channel form. In general, we expect landslides and tree mortality to be the dominant LWD inputs in steep-gradient, confined, bedrock or coarse-textured channels with steep valley sideslopes while bank erosion will increase in importance in lower-gradient, unconfined, alluvial channels with broader valley flats. As a result, the lateral distances over which LWD originates will vary with channel type and size. The local influences of topography, connectivity, and tree mortality may modify these expectations, however (Benda et al. 2002, Reeves et al. 2003).

Variation in LWD functioning among channel types

Structural elements such as clasts, individual LWD pieces, or LWD accumulations whose dimensions are large relative to channel dimensions often exert a controlling influence on the morphology of alluvial channels (Church 1992, Gurnell et al. 2002) by altering local sediment transport and deposition. The importance of LWD pieces as channel-shaping agents will depend on their size and abundance relative to other large roughness elements within the channel. It will also vary with factors such as channel gradient, width-to-depth ratio, grain size relative to flow depth, and the size and rate of supply of bed material (Buffington et al. 2002). Steep-gradient channels in mountainous terrain (i.e., step-pool and cascade-pool channel types) generally have a capacity to transport sediment that is high relative to sediment supply (Montgomery and Buffington 1997). Large clasts or stone lines that are immobile except at extreme flows form important components of the bed material of such channels and are often the structural elements that determine channel morphology. LWD may have only a minor influence on channel morphology in steep-gradient channels (Montgomery et al. 1995, Anonymous 1996, Berg et al. 1998, Warren and Kraft 2003), although channel-spanning pieces may form steps that induce “forced” riffle-pool morphology if sediment inputs are sufficient (Montgomery et al. 1996, Faustini and Jones 2003), and channel width may increase with the frequency of flow obstructions (Jackson and Sturm 2002).

In small, constrained channels much of the LWD may lie above the active channel and have no immediate geomorphic effect (Halwas and Church 2002, Chen et al. 2006). These steep-gradient channels typically have erosion-resistant banks, high depth-to-width ratios, and high connectivity to hillslopes (Montgomery and Buffington 1997). Consequently, LWD inputs are dominated by landslides and tree fall (Lienkaemper and Swanson 1987, May and Gresswell 2003, Montgomery et al. 2003). The steep sideslopes and high connectivity increase LWD loadings per unit stream length by increasing the recruitment area for woody debris per unit horizontal distance (Jackson and Sturm 2002).

LWD pieces that are stable in low-gradient, riffle-pool channels are considerably larger than the bed material, and can greatly alter channel morphology by causing localized scour and deposition. Mean pool spacing (Montgomery et al. 1995), pool area (Hogan 1986, Buffington et al. 2002), variability in channel width and depth (Hogan 1986), and sediment storage (Bilby and Ward 1989) all increase with increasing LWD loading in low-gradient channels. Low-gradient riffle-pool channels are characterized by lower depth-to-width ratios, smaller and more-easily mobilized bed materials, and well-developed alluvial floodplains (Montgomery and Buffington 1997). Banks of fluvially deposited materials and reduced connectivity with hillslopes result in undercutting and bank erosion being relatively more important as LWD delivery mechanisms in these channels.

The stability and geomorphic functioning of a LWD piece will be influenced by both channel type and channel size. At a given channel width, the steeper gradient and greater depth-to-width ratio of a step-pool or cascade-pool channel compared to a riffle-pool channel should result in higher stream power, greater submergence, higher obstruction ratio, and higher net forces on a LWD piece of a given size. Thus, the minimum size of a stable LWD piece is expected to be larger in the steeper gradient channels than in a riffle-pool channel of the same width. The mean size of functional LWD also increases with channel width (Likens and Bilby 1982, Bilby and Ward 1989, Chen et al. 2006), presumably because increased stream power removes small wood. Other things being equal, a smaller proportion of woody debris inputs will be geomorphically functional at a steep gradient channel than at a similar-size riffle-pool channel, and the steeper channel will export more small wood to downstream reaches.

In general, the effect of LWD on channel structure is expected to be greatest in small to medium-sized, low-gradient stream reaches (Anonymous 1996). Although pool formation in small steep-gradient streams can be influenced by LWD (Montgomery et al. 1995), and the rate of change of pool spacing with increasing LWD loading is greater in moderate-gradient streams than in low-gradient streams (Beechie and Sibley 1997), pool numbers and area at a given loading nevertheless are greatest in low-gradient streams (Beechie and Sibley 1997, Buffington et al. 2002). The upslope delivery mechanisms (debris flows, landslides) that are relatively more common at constrained, steep-slope reaches introduce woody debris which is considerably smaller than that originating from streamside mechanisms (Reeves et al. 2003). A higher incidence of bank erosion at riffle-pool channels should result in a greater frequency of large piece sizes (e.g., whole trees with root-wads) entering than at step-pool and cascade-pool channels

Table 1. Widths of the "zone of sensitivity" for the delivery of large woody debris as specified under the Riparian Area Regulations of the Fish Protection Act. Note that widths are horizontal distances, not slope distances.

Channel type [a]	Vegetation type		
	Low cover	Shrub	Trees
riffle-pool	3 times the channel width, to a maximum of 5 m	3 times the channel width, to a maximum of 20 m	3 times the channel width, with a minimum of 10 m and a maximum of 30 m
cascade-pool	2 times the channel width, to a maximum of 5 m	2 times the channel width, to a maximum of 10 m	2 times the channel width, with a minimum of 10 m and a maximum of 15 m
step-pool	1 times the channel width, to a maximum of 5 m	1 times the channel width, to a maximum of 10 m	10 m

[a] Channel types follow the "Channel assessment procedure field guidebook" (Anonymous 1996) of the B.C. Forest Practices Code. Note that the CAP definitions of channel types may differ from similarly-named channel types under other widely-used classifications (e.g., Montgomery and Buffington 1997).

for the same vegetation density and size. Because the geomorphic impact of LWD (pool size, sediment storage) increases with piece size (Bilby and Ward 1989) and LWD abundance per unit stream length is highest in low-gradient, unconfined channels (Martin 2001, Fox and Bolton 2007), low-gradient alluvial channels are expected to be strongly influenced by LWD inputs. Moreover, large wood pieces that are well-anchored (e.g., by root-wads) can act as key pieces (Abbe and Montgomery 2003) that accumulate smaller pieces in transport to form stable logjams which may alter channel morphology over very long distances in low-gradient channels (Hogan et al. 1998). Experimental additions and removals of LWD in small streams generally show that the presence of LWD alters channel structure in low-gradient streams but has little effect in mid- and high-gradient streams (Hilderbrand et al. 1997, Roni et al. 2002, Warren and Kraft 2003, Sweka and Hartman 2006); effects on invertebrates and fish are variable (Wallace et al. 1995, Hilderbrand et al. 1997, Roni et al. 2002).

Management agencies often vary the prescribed widths of riparian buffers with site characteristics such as stream size, gradient, and vegetation type, among others (Young 2000, Blinn and Kilgore 2004, Lee et al. 2004). Although prescribed buffer widths often address concerns other than the provision of LWD (Fischer and Fischenich 2000), reduced buffer widths on small, high gradient, and/or non-fish bearing streams may implicitly reflect beliefs about input mechanisms for and the functional role of LWD in such streams. For example, the widths of riparian buffers to provide LWD prescribed by the Riparian

Area Regulations of the B.C. Fish Protection Act vary with stream channel type, bankfull width, and riparian vegetation type (Table 1). The matrix framework recognizes the (potentially) differing delivery processes for and functional roles of LWD in forested streams with different channel types and sizes. The regulations thus contain implicit hypotheses about the processes that influence LWD inputs and function. Although the above discussion suggests that the source distance and functional importance of LWD within a stream may vary with channel type and size, the hypotheses need to be tested formally against empirical data. This review examines and, where possible, tests these hypotheses.

We use published or Internet-accessible grey literature measurements of the variation in cumulative inputs of functional LWD with lateral distance from the channel margin ("LWD source distance curves") to test the hypothesis that LWD source distances vary among stream channel types, stream size, and vegetation height. We did not test the hypothesis that the functional importance of LWD is reduced in channel types that are characterized by high relative roughness from non-wood sources, i.e., that non-wood obstructions account for most of the observed local variation in channel morphology, because data appropriate to formal statistical tests are rare.

Methods

Data sources

We obtained published and Internet-accessible grey literature measurements of LWD source distance curves by searching electronic databases (Web of Science) and primary journals in forestry, fisheries, and geomorphology in which source distance curves were known to have been published. We also searched the Internet using Google and Google Scholar. We found 137 source distance curves from 13 separate studies (Table 2), most from streams in coniferous forests along the Pacific coast of the U.S.A.

All studies defined functional LWD by piece size rather than by geomorphic effect, but the minimum size criteria for inclusion as functional LWD varied considerably among studies (Appendix 1), from a piece length of 0.5 m and a diameter of 0.05 m at the basal end (Dahlström and Nilsson 2006) to 3 m x 0.1 m (Murphy and Koski 1989). In some cases, it was not clear how the size criteria were applied. LWD definitions were not reported or not available for McKinley (1997), Reid and Hilton (1998), and Rex et al. (2006). All studies except for Dahlström and Nilsson (2006) determined source distance by direct measurement of the distance from tree origin to the stream margin for those LWD pieces whose origins were identifiable. McDade et al. (1990), May and Gresswell (2003), and Benda et al. (2002) determined slope distance, but all other studies appear to report horizontal distance. Note that McDade (1987) reported horizontal distance, while McDade et al. (1990) reported slope distance. The proportion of instream LWD pieces for which source distance could be determined varied from 11% to 78% among studies (Appendix 1), with a median value of 52% for 9 data sets. Only 6 of the 13 studies reported this information, but two studies reported the proportion separately for different locations within the study.

LWD source distances curves were usually based on the cumulative numbers of LWD pieces originating within specified distances from the stream edge. Nine studies used cumulative numbers of LWD pieces to construct source distance curves, two used cumulative volumes, and two studies reported both. Most studies pooled data from multiple sites to create a composite LWD source distance curve or curves, but four studies (McDade (1987), Martin et al. (1998), Benda et al. (2002), and Lee Benda and Associates (2003)) presented separate source distance data for individual sites. These four studies accounted for 114 of the 117 individual site data. McDade et al. (1990) reported a pooled curve but the raw data for the study are available from the H.J. Andrews Experimental Forest Long Term Ecological Research website. We used these raw data to construct source distance curves for both the cumulative number of LWD pieces and the cumulative volume of pieces for each of the 39 sites in McDade's study. We estimated volumes of the within-channel portions of individual pieces from their reported dimensions, assuming a cylindrical shape. This assumption appears reasonable because most pieces were tree stems and the within-channel portions usually were small proportions of the whole pieces. Murphy and Koski (1989) and Martin et al. (1998) gave cumulative percentages to particular distances (e.g., < 1 m, 1-5 m, 6-10 m, etc.); we approximated source distance curves by plotting cumulative percentages against the upper bound of the intervals and interpolating between points.

Stream channel widths and slopes were variously reported for individual stream reaches or as means for groups of reaches (Appendix 1). Tree height data for the riparian forest were usually reported as a mean (or median) from multiple sites rather than as site-specific values; we applied the reported value to all sites in a group. Tree heights appeared to refer to the overstory dominants rather than to all trees capable of contributing LWD. Six studies identified the processes by which LWD pieces had entered the streams (Appendix 1). These data were usually reported as relative proportions by input mechanism, pooled over multiple sites.

Analyses

We determined graphically (from published or constructed LWD source distance curves) the lateral distances that supplied specified proportions (e.g., 50%, 75%, 80%, 90%, 95%) of the cumulative numbers or volume of LWD pieces. Where possible, we expressed distances as absolute (metres) and relative (proportion of mean tree height) values. Because regulations usually specify mandatory buffers as absolute widths (Lee et al. 2004), we determined the proportion of cumulative LWD values at particular distances (e.g., 10 m, 30 m) that commonly appear in regulations.

We organized the available data into channel type and stream width categories that corresponded to those used in the Riparian Area Regulations (Table 1). We used the channel width, channel slope, substrate, and channel type information provided by authors to re-classify streams according to the Channel Assessment Procedure (Anonymous 1996) channel typology that is used in the Riparian Area Regulations (i.e., riffle-pool, "RP"; cascade-pool, "CP"; and step-pool, "SP", Table 1). We used mean bankfull channel width (w_b) to classify streams into small ($w_b < 3.33$ m, "S"), medium ($3.33 \text{ m} \leq w_b < 10$ m, "M"), or large ($w_b \geq 10$ m, "L") width categories that correspond to thresholds at which mandatory

Table 2. Published and Internet-accessible unpublished sources for large woody debris source distance curves.

ID code	Citation	Source	Geographic location	No. SDC[a]	Riparian tree species
MK	Murphy and Koski (1989)	North Am. J. Fish. Mgmt. 9: 427-436	Alaska (SE and Kenai Peninsula)	6[b]	Sitka spruce Western hemlock
McD	McDade et al. (1990)	Can. J. For. Res. 20: 326-330	Oregon and Washington (Cascades and Coast Range)	39	Douglas fir Western hemlock Red cedar
McK	McKinley (1997)	Unpublished report, University of Washington, College of Forest Resources	Washington (Cascades)	1[c]	Douglas fir Western hemlock Red cedar Amabilis fir
RH	Reid and Hilton (1998)	USDA Forest Service report PSW-GTR-168: 71-80	California (Caspar Creek)	2[d]	Redwood Douglas fir
MRG	Martin et al. (1998)	Unpublished report, Sealaska Corporation and Alaska Forest Association	Alaska (SE)	38	Western hemlock Sitka spruce
GMSB	Grizzel et al. (2000)	Washington Department of Ecology, report TFW-MAG1-00-003	Washington (North Cascades)	3[e]	Western hemlock Douglas fir Red cedar Red alder Bigleaf maple Amabilis fir
BBW	Benda et al. (2002)	Can. J. For. Res. 32: 1460-1477	California (Humboldt Bay area)	17[f]	Redwood Douglas fir
Opp	Opperman (2002)	Ph.D. thesis, University of California, Berkeley	California (Russian River area)	2[g]	White alder Bay laurel Willows Douglas fir Redwood Oaks
MG	May and Gresswell (2003)	Can. J. For. Res. 33: 1352-1362	Oregon (Coast Range)	2[h]	Douglas fir Western hemlock

Table 2. (continued)

ID code	Authors	Citation	Location	No. SDC[a]	Riparian tree species
PLC	Pacific Lumber Company (2003)	Unpublished report, Freshwater Creek Watershed Analysis, Appendix E: Stream channel assessment	California (Humboldt Bay area)	1[i]	Redwood
LBA	Lee Benda and Associates, Inc. (2004)	Unpublished report for Campbell Timberland Management	California (Humboldt Bay area)	21	Redwood Douglas fir
BRM	Rex et al. (2006)	Unpublished public presentation, BC Ministry of Forests	BC (Prince George Forest District)	3	Hybrid white spruce Subalpine fir Lodgepole pine
DN	Dahlström and Nilsson (2006)	Can. J. For. Res. 36: 1139-1148	Central Sweden	2[j]	Norway spruce Scotch pine

[a] Number of LWD source distance curves (“SDC”) reported.

[b] The 6 reported SDCs are pooled data from 32 reaches within 6 stream channel classes.

[c] A single SDC is reported for multiple stream reaches (number of sites unknown).

[d] The 2 reported SDCs pool data from 17 sites.

[e] The 3 reported SDCs pool data from 10 sites, based on riparian buffer widths.

[f] Data for 5 old-growth sites were pooled into a single reported SDC, but individual SDCs were reported for 16 second-growth sites.

[g] The 2 reported SDCs pool data from 30 sites.

[h] Data for 3 second-order sites were pooled into a single SDC. Distances were slope distance rather than perpendicular distance.

[i] A single SDC is reported from 23 stream reaches.

[j] A single SDC was reported from each of 13 old-growth sites and 11 managed second-growth sites.

buffer widths for LWD inputs change for forested riffle-pool channels under the Riparian Area Regulations (Table 1). Because McDade (1987) gave channel widths for only 4 of 39 sites but provided stream order information for all sites, we used the four sites with complete information as a guide to categorize sites that lacked w_b data, as "S" for order 1 and 2 sites and as "M" for order 3 sites. Few data sets provided complete coverage of all the variables that we wished to examine (Appendix 2), so different analyses can be based on different subsets of the data. Channel widths varied between 0.9 and 31.4 m. Tree heights varied between 23 and 65 m, but coverage was very uneven within the range, with most tree heights being near 30 m or near 60 m.

We used box-and-whisker plots and quantile plots to summarize cumulative distributions of source distances within categories of channel type and width. For large random samples, the quantiles approximate the distribution of the data and can be used to identify source distances within which specified proportions of the cumulative LWD inputs occur with a specified probability. For example, in the upper left panel of Fig. 2a, the 75th quantile of the distribution of the distances within which 90% of the cumulative inputs of LWD volume originated was about 14 m. Thus, there was (approximately) a 0.75 probability that a 14 m buffer would provide 90% of the expected cumulative inputs of LWD by volume for a riffle-pool channel drawn at random from the domain of the sampling. Quantile plots allow resource managers to make probabilistic assessments of the ability of particular measures (e.g., buffer widths) to attain a specified management objective; they require, however, that manager specify both the objective and the acceptable risk (e.g., "to assure 90% of the cumulative inputs of LWD by volume with 75% probability"). We did not weight source distances by sample size where data from multiple sites had been summarized as a single source distance curve.

We used analysis of covariance (ANCOVA) to test whether channel type, channel width, and tree height influenced the source distances needed to provide specified proportions of cumulative LWD inputs. Because some studies had information on LWD input mechanisms, we repeated the analysis with the dominant input process (i.e., the process that accounted for the largest proportion of the cumulative LWD input) as a categorical variable to test whether this information improved the fit obtained from channel type, channel width, and tree height. To avoid empty cells, we combined cascade-pool and step-pool channel types into a single "steep gradient" channel category. Channel width and tree height were treated as covariates because they were continuous variables. We used the source distance within which 90% of the cumulative LWD inputs originated as the dependent variable because it is less influenced by ill-defined extrema in small samples than are higher (95% or 99%) levels. We report analyses for both cumulative numbers and volume of LWD pieces, however, source distance data for numbers of LWD pieces were too sparse for some combinations of explanatory variables (Appendix 2) to provide meaningful comparisons, and these results should be viewed cautiously. Source distances were logarithm-transformed to conform better to the normality and homogeneity of variance assumptions of the parametric analyses. For factorial models or those including covariates, we first tested for the presence of interactions and/or homogeneity of slopes by including all first-order interactions in the model. We then tested for main effects (or homogeneity of intercepts) on a reduced model that omitted non-significant interactions. We used $\alpha = 0.10$

to assess treatment effects in these exploratory analyses. Where appropriate, we compared levels of main factors adjusted for covariates using Tukey’s test at α = 0.10.

Results

Cumulative distributions of numbers or volumes of LWD inputs by source distance at individual stream reaches varied considerably among sites within geographical areas with similar vegetation types and topography (e.g., Fig. 1). Cumulative distributions were concave typically, rising steeply as lateral distance increased but with long tails of small inputs from longer distances (Fig. 1). Where both volume and numbers of LWD inputs were estimated, the lateral distance to attain a specified proportion of the cumulative volume of LWD inputs was generally less than that for the same proportion of the cumulative numbers of pieces. For example, the 90th percentile of cumulative volume occurred significantly closer to the stream than that of numbers (paired t-test, mean difference = 3.85 m, $t = 3.28$, $df = 40$, $P = 0.002$).

Quantile plots of the source distances within which specified proportions of the cumulative distributions of LWD inputs occurred (Fig. 2a and 2b) showed that the median distance within which 90% of the cumulative volumes of LWD originated was 7 to 23 m (0.36 to 0.85 mean tree heights, mth) from the stream for the three channel types. Note, however, the small samples sizes for cascade-pool and step-pool channels. The quantile plots also suggested that the source distances to attain specified proportions of the cumulative distribution of LWD volumes were reduced at riffle-pool channels. Sample sizes were too small for all channel types to provide reliable estimates of the median distances for numbers of LWD pieces.

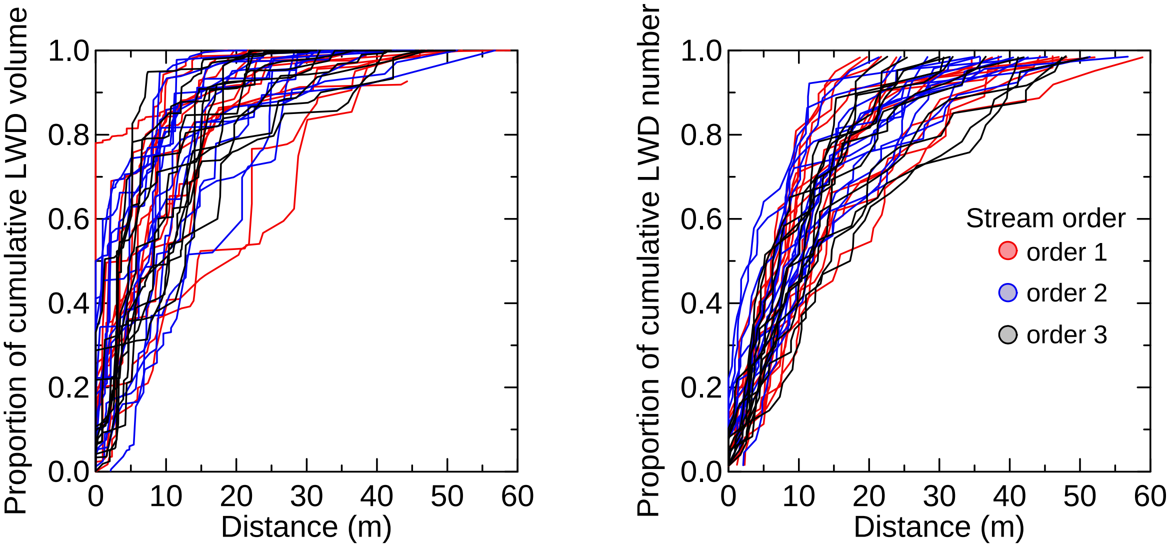

Figure 1. Cumulative inputs by volume (left panel) or number (right panel) of large woody debris (LWD) pieces originating at different lateral distances from the channel (“LWD source distance curves”) for individual reaches on first-order through third-order streams in old-growth or mature second-growth Douglas fir / western red cedar forests in the western Cascades Range of Oregon and Washington. Source distance curves were calculated from the data of McDade (1987). Note the concave shape of most of the individual source distance curves. Some of the variation may be attributable to differences among sites in characteristics that influence input processes.

Quantile plots of cumulative LWD inputs suggested that source distances were influenced by the nature of the dominant LWD delivery mechanism (Fig. 3a and 3b). The median source distances for 90% of the cumulative LWD volume inputs varied between 6 to 20 m (0.24 to 0.74 mth) for the three dominant delivery mechanisms but was considerably reduced (6 m) where bank erosion was identified as the dominant input mechanism. In most cases, however, several input mechanisms contributed to LWD delivery (Appendix 1).

Tree height strongly influenced the source distance within which 90% of the cumulative numbers and volume of LWD inputs originated (Tables 4 and 5; also see Appendix 3). The influence of channel type on source distance depended on channel width, i.e., there was an interaction between the factors (Table 4). Source distances at riffle-pool channels did not appear to vary with channel width but source distances increased with channel width at cascade-pool and step-pool channels (Fig. 4). Fig. 4 also suggested that LWD source distances for small channels varied little among channel types. Information on the dominant LWD delivery process improved model fit to source distances for the 90% of cumulative volume inputs (Table 5). Source distances, adjusted for covariates, when tree fall (i.e., tree mortality and windthrow) was identified as the dominant delivery process were greater than those for bank erosion or landslides (Tukey's hsd test, $P = 0.045$), which did not differ (Tukey's test, $P = 0.13$).

Discussion

Factors influencing LWD source distances

The lateral distance from which functional large woody debris enters a stream is influenced by the mechanical processes through which wood is mobilized and delivered to the stream, as well as by characteristics of the riparian forest. While some field studies have noted that recruitment distances for LWD can vary greatly with the delivery mechanism (Benda et al. 2002, May and Gresswell 2003), models of the recruitment process have generally emphasized tree fall as the dominant delivery mechanism (Van Sickle and Gregory 1990, Bragg 2000, Welty et al. 2002) and therefore focus on tree height as a key determinant of expected recruitment distances. While our analysis confirmed an important effect of tree height on recruitment distances, delivery mechanism also accounted for a large proportion of the variance in empirical data. At sites where bank erosion was identified as the dominant recruitment mechanism, source distances for LWD volume were considerably less than at sites where tree fall dominated. This is, of course, unsurprising because bank erosion is a near-channel process and because the dimensions of wood entering the channel are expected to increase with proximity to the channel if tree size is not correlated with distance from the channel. Nevertheless, the occurrence of bank erosion will shift LWD sources towards shorter distances than would be expected from vegetation characteristics.

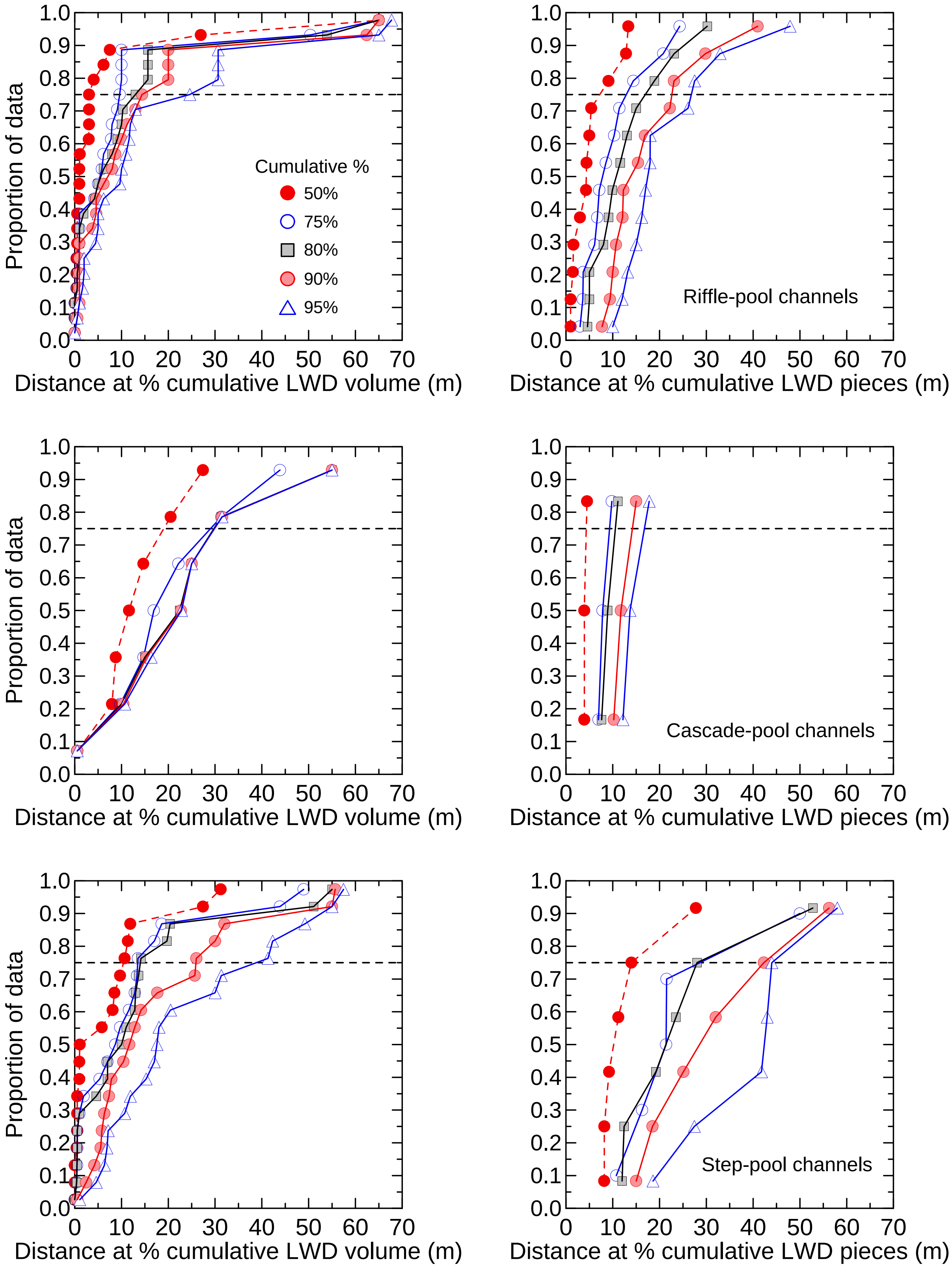

Figure 2a. Quantile plots of the source distances (m) within which specified proportions of the cumulative inputs by volume (left panel) or number (right) of large woody debris (LWD) pieces originated at different channel types.

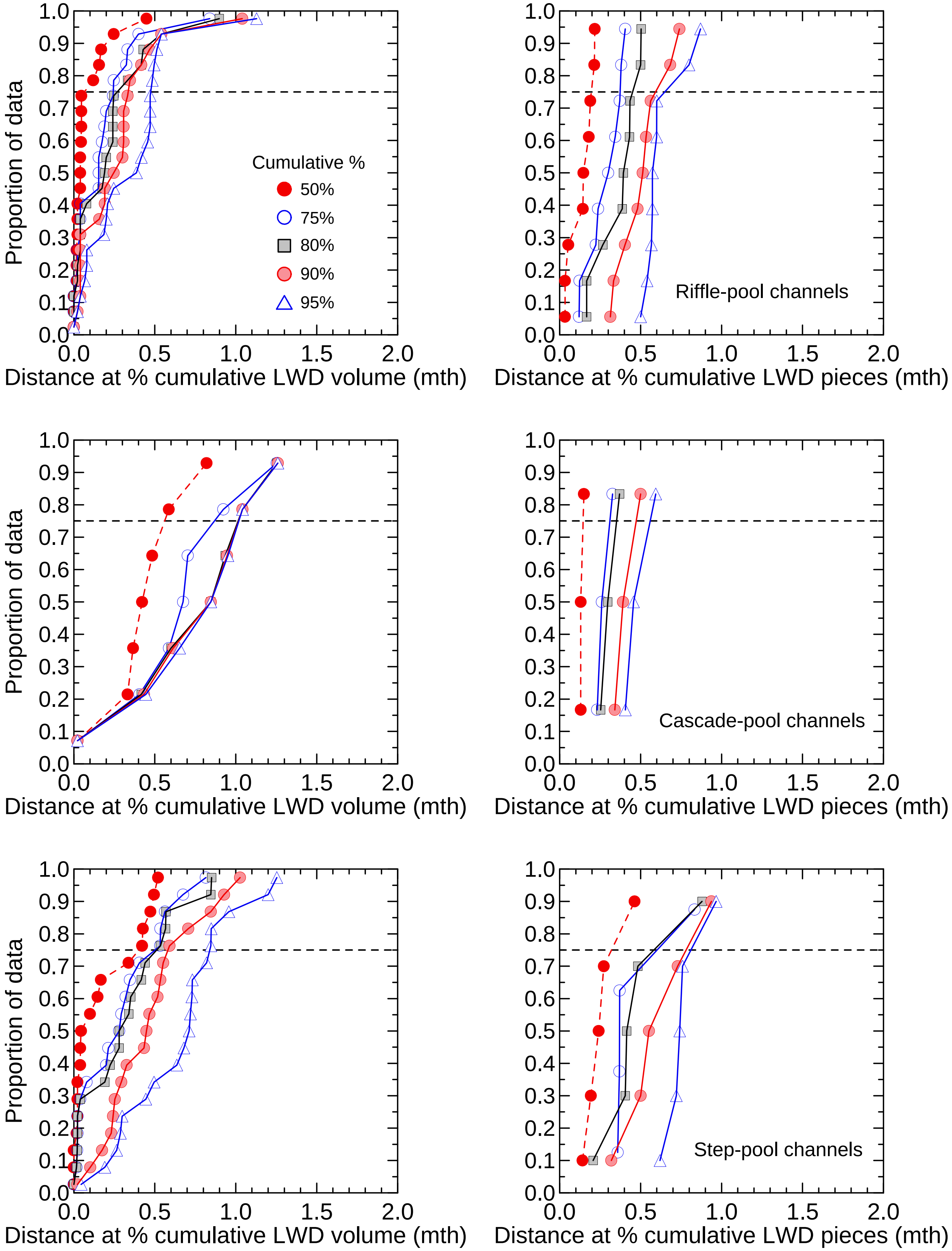

Figure 2b. Quantile plots of the source distances (units of mean tree heights) within which specified proportions of the cumulative inputs of large woody debris (LWD) volume or numbers originated at different channel types.

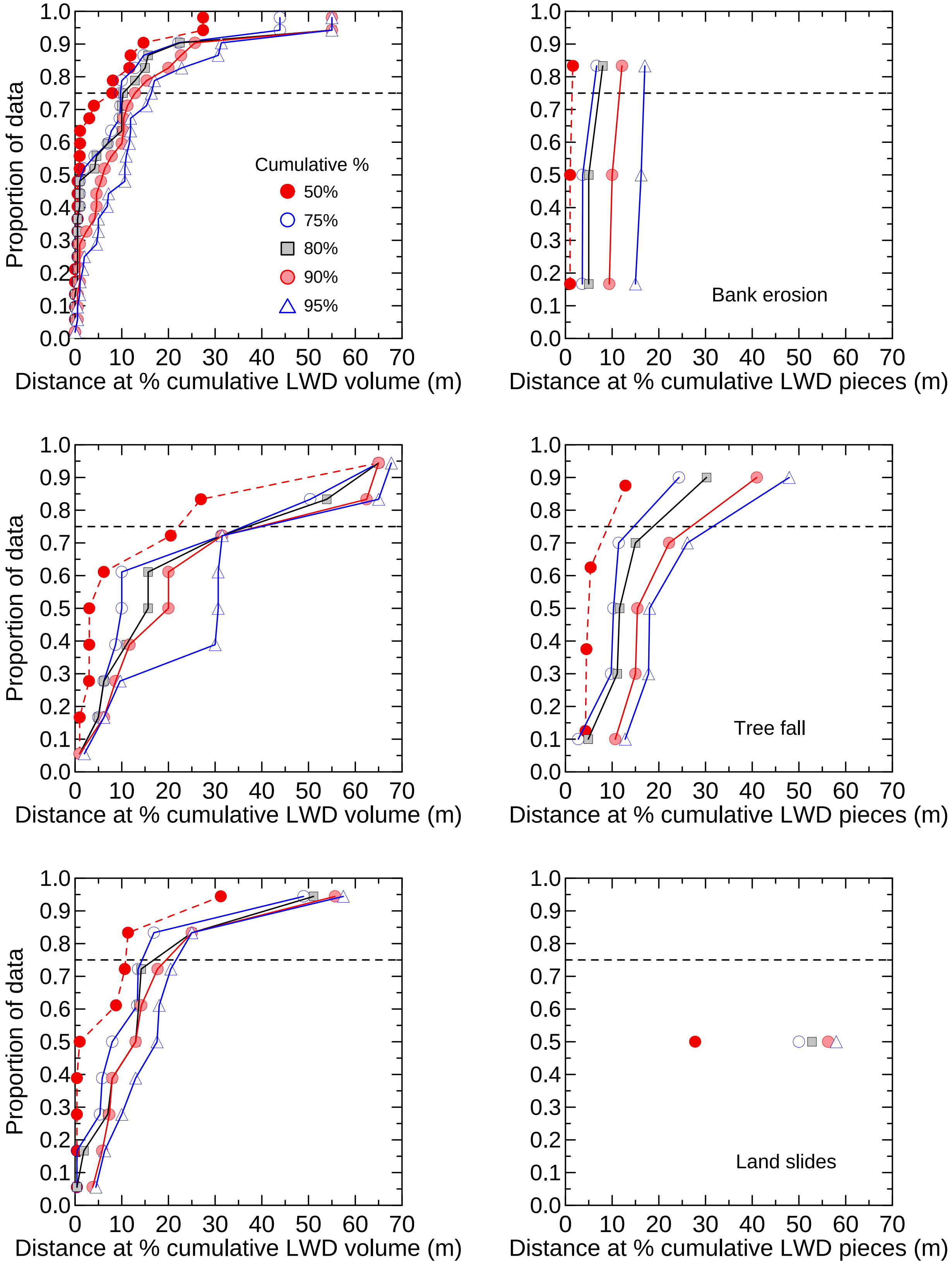

Figure 3a. Quantile plots of the source distances (m) within which specified proportions of the cumulative inputs of large woody debris (LWD) volume or numbers originated for different dominant input mechanisms.

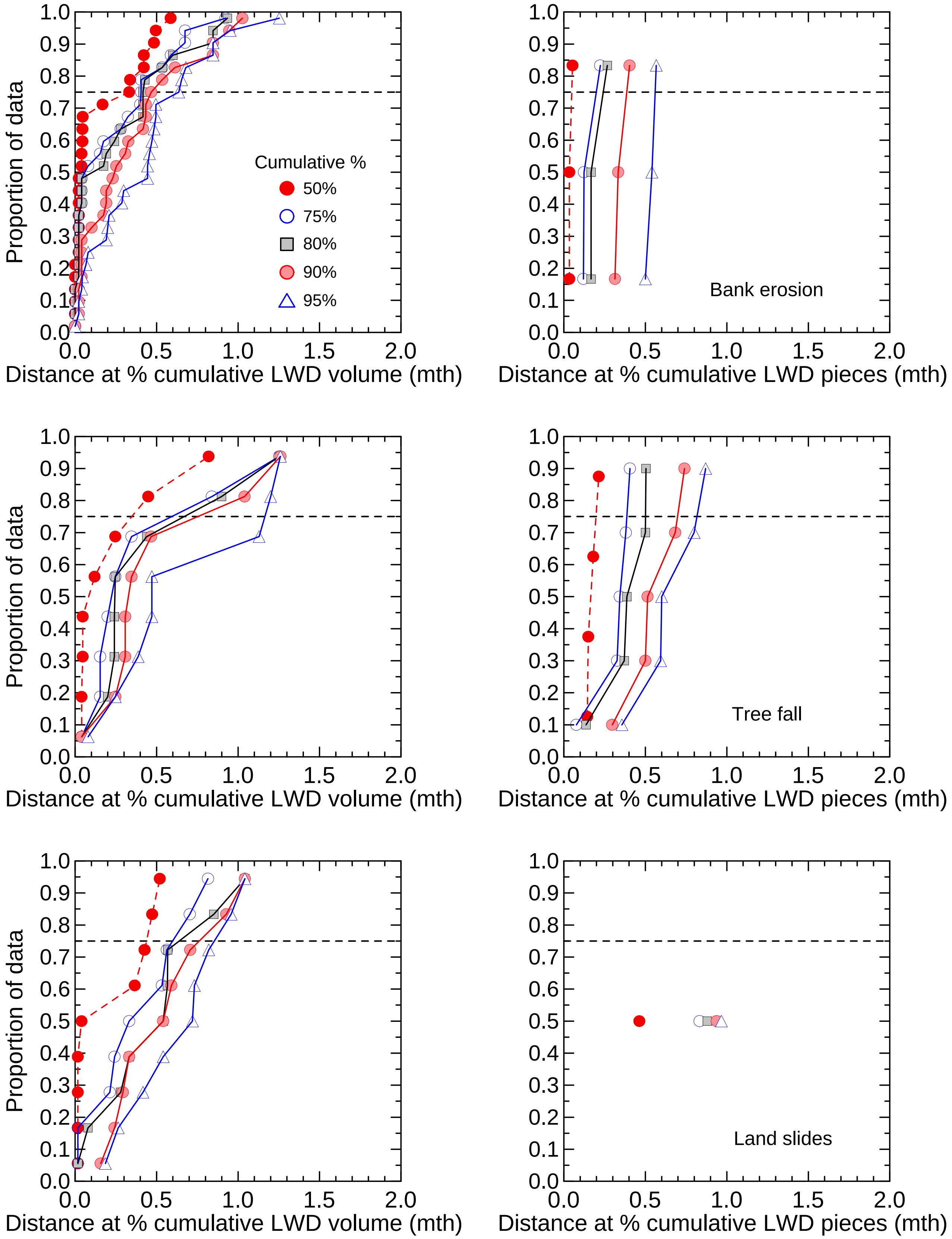

Figure 3b. Quantile plots of the source distances (mean tree heights) within which specified proportions of the cumulative inputs of large woody debris (LWD) volume or numbers originated for different dominant input mechanisms.

Table 3. Effects of channel type, bankfull channel width and tree height on the distance (m) within which 90% of the cumulative number of large woody debris pieces originated. $R^2 = 0.74$ ($N = 17$) for the model:

$$\log_{10}(\text{Source distance}) = \text{Constant} + \text{Channel type} + \text{Channel width} + \text{Tree height}$$

Factor	Sum of squares	*df*	*MS*	*F*	*P*
Channel type[a]	0.009	1	0.009	0.532	0.479
Channel width[b]	0.014	1	0.014	0.767	0.397
Tree height[c]	0.576	1	0.576	32.428	< 0.001
Error	0.231	13	0.018		

[a] Riffle-pool or (cascade-pool / step-pool) channels (categorical variable with 2 levels).

[b] Bankfull channel width in m (continuous variable).

[c] Mean tree height in m (continuous variable).

Table 4. Effects of channel type, bankfull channel width and tree height on the distance (m) within which 90% of the cumulative volume of large woody debris pieces originated. $R^2 = 0.42$ ($N = 47$) for the model:

$$\log_{10}(\text{Source distance}) = \text{Constant} + \text{Channel type} + \text{Channel width} + \text{Tree height} + \text{Channel type} \times \text{Channel width}$$

Factor	Sum of squares	*df*	*MS*	*F*	*P*
Channel type[a]	0.024	1	0.024	0.112	0.739
Channel width[b]	0.005	1	0.005	0.022	0.882
Tree height[c]	3.442	1	3.442	15.995	0.001
Channel type × channel width	0.728	1	0.728	3.381	0.073
Error	9.037	42	0.215		

[a] Riffle-pool or (cascade-pool / step-pool) channels (categorical variable with 2 levels).

[b] Bankfull channel width in m (continuous variable).

[c] Mean tree height in m (continuous variable).

The variation in LWD (volume) source distance with channel type and size suggests that these factors provide information about delivery mechanisms. Channel type and size influenced LWD recruitment distances, but the effect of stream size varied with channel type. In general, stream size had little effect on LWD recruitment distances for riffle-pool channels. This observation may reflect a greater role for bank erosion at alluvial channels, whose banks are composed of fluvially-deposited sediments that are relatively more easily mobilized than non-alluvial materials. LWD recruitment distances were roughly similar among channel types for very small streams, but increased with stream size for the steeper gradient channel types. Large steep-gradient channels may cut gullies with relatively steep side-slopes which may facilitate the delivery of LWD to the channel by downslope tree fall (Sobota et al. 2006) and land slides over greater lateral distances than from the flatter alluvial benches that are more characteristic of riffle-pool channels. While the inclusion of channel type and size information improved estimates of LWD source distances, direct knowledge of the dominant LWD delivery process at a site further improved model fit.

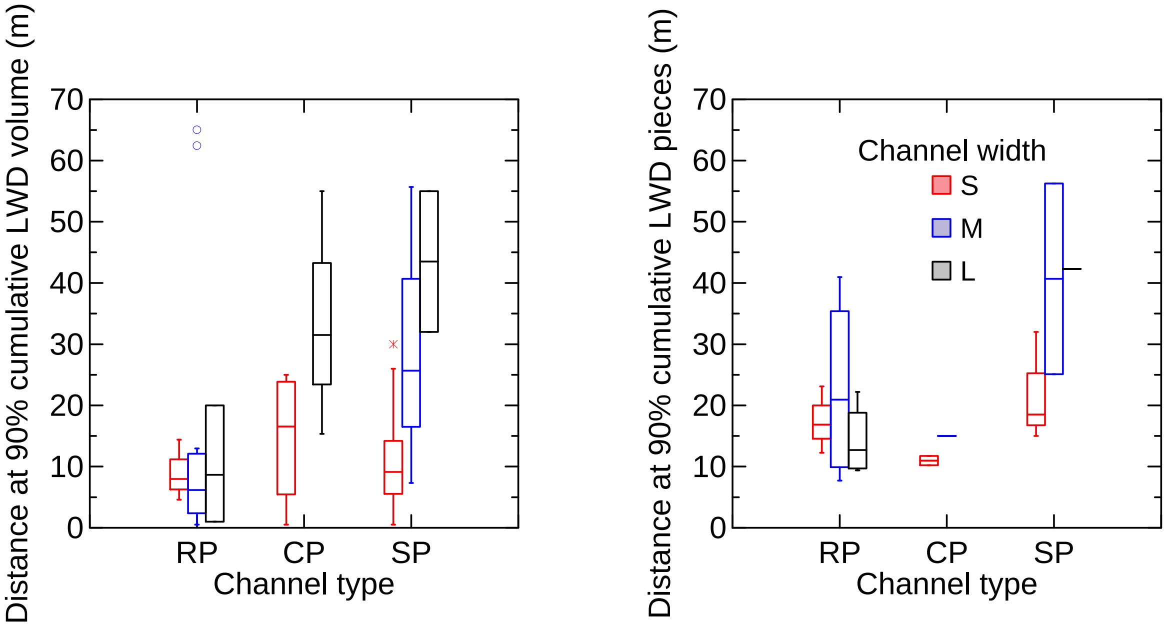

Figure 4. Box-and-whisker plots of the variation with channel type and channel width of the source distance within which 90% of the volume (left panel) or number (right panel) of large woody debris (LWD) pieces originate. Note the interaction between channel type and channel width for volume inputs. Channel types are riffle-pool (RP), cascade-pool (CP), and step-pool (SP). Channel width categories are <=3.33 m (S), 3.33 to 10 m (M), and > 10 m (L). The horizontal line is the sample median, the box edges are the 25% and 75% quartile and the whiskers encompasses values within 1.5 times the interquartile range of the edges. Asterisks indicate outliers, and dots indicate extreme values.

Table 5. Effects of dominant delivery mechanism, channel type, bankfull channel width and tree height on the distance (m) within which 90% of the cumulative volume of large woody debris pieces originated. $R^2 = 0.51$ ($N = 43$) for the model:

$$\log_{10}(\text{Source distance}) = \text{Constant} + \text{Delivery mechanism} + \text{Channel type} + \text{Channel width} + \text{Tree height} + \text{Channel type} \times \text{Channel width}$$

Factor	Sum of squares	*df*	*MS*	*F*	*P*
LWD[a] delivery mechanism[b]	1.708	2	0.854	4.276	0.022
Channel type[c]	0.020	1	0.020	0.100	0.754
Channel width[d]	0.015	1	0.015	0.077	0.783
Tree height[e]	2.206	1	2.206	11.043	0.002
Channel type × channel width	0.924	1	0.924	4.624	0.038
Error	7.190	36	0.200		

[a] Large woody debris.

[b] Bank erosion, tree fall, or land slides (categorical variable with 3 levels).

[c] Riffle-pool or (cascade-pool / step-pool) channels (categorical variable with 2 levels).

[d] Bankfull channel width in m (continuous variable).

[e] Mean tree height in m (continuous variable).

Potential biases in survey data

Our analyses and interpretations may be subject to several important biases. First, although we assembled and used all accessible LWD source distance curves, our analyses of the effects of factors that influence LWD recruitment distances were constrained by the availability of data. Many studies did not report data for factors which are expected to influence LWD recruitment and whose effects we wished to examine. Certain combinations of factors were poorly represented in the data available to us (Appendix 2). Thus, our quantitative results are derived from a small subset of the empirical studies, often from particular geographic areas whose vegetation, climate, geology, and topography may not be representative of the region to which we wish to apply our results. Unless appropriate data are collected from numerous sites in British Columbia, we cannot easily improve upon the current analyses.

Second, LWD recruitment is usually determined from a single survey and so may not integrate over time intervals that are appropriate to indicate the relative importance of LWD delivery mechanisms. Major inputs of LWD are often episodic (Hogan et al. 1998), and may occur through different mechanisms than chronic inputs. Depending on the relative frequency of different delivery mechanisms, certain processes may be over- or under-represented in data from a single survey.

Third, the common operational definitions of LWD using fixed size criteria (e.g., wood greater than 10 cm in diameter and 1 metre in length in contact with the active channel) independent of the dimensions of a channel or its roughness elements may result in the variable exclusion from the source distance curve of a portion of the wood that actually functions to alter the morphology of the stream. Although it is recognized that inconsistent or inappropriate definitions of functional LWD may plague comparisons among studies (Hassan et al. 2005), no one has assessed the effects of alternative operational definitions of LWD on empirical source distance curves. The heterogeneity of the LWD definitions occurring in the data sets that we used (Appendix 1) will inflate variances and obscure relationships to predictor variables.

Fourth, to represent the source distance curve accurately the LWD pieces whose origins are determined must be a random sample from the distribution of source distances. Empirical determinations of LWD source distances can usually identify the origins of only a small subset of the LWD that is present at a site. If the ability to identify the origin of a LWD piece varies systematically with distance from the channel, source distance curves will be distorted. For example, LWD source distances may be more easily determined for large, well-anchored, near-bank contributions than for smaller pieces originating at greater distances, or for certain processes (e.g., whole-tree delivery via erosion versus fragmented pieces from tree fall).

We can envisage several mechanisms that might result in non-random sampling of the distribution of LWD source distances. The first mechanism is selection bias, in which LWD from the whole range of source distances is available to be sampled but the field protocol used by the researcher differentially samples (or omits) wood originating at particular distances. For example, large logs with attached root wads that originate near the channel might be over-sampled because of their high visibility and obvious origins, or small pieces originating at long distances might be under-sampled because of an inappropriate restriction on the distance from the channel within which tree origins are sought. Selection bias is largely avoidable by carefully following well-defined sampling protocols, and should rarely occur.

A second mechanism that would result in non-random sampling of source distances is the removal from the pool of LWD available to be sampled of pieces that originate at particular distances from the channel. Removal of LWD from the pool of pieces whose origin can be traced will occur if pieces are displaced from their point of entry or decay so that they cannot be connected to a rooting location. Both decay and displacement by flows will be piece-size dependent, with smaller LWD pieces being differentially removed from the sampling domain. Which pieces comprise the “small” (i.e., fluvially-transportable) component of the LWD depends on their sizes relative to channel dimensions (Braudrick et al. 1997, Braudrick and Grant 2000, Abbe and Montgomery 2003). The effect on source distance curves depends upon the origins of the “small”, transportable pieces.

Where landsliding is not an important delivery process, small pieces of LWD will enter the channel either as small trees originating near the channel, as fragments of large trees originating near the channel which break on entry, or as the upper portions of large trees originating far from the channel. If tree height is not correlated with distance from the channel, the relative importance of these three sources of small LWD will depend upon the relative abundances and mortality rates of small and large trees within the riparian zone. In undisturbed mature and old-growth conifer forests in B.C. and the nearby U.S.A., the abundance of smaller trees is generally considerably greater than those of larger trees (Franklin and Debell 1988, LePage 1995, Parish et al. 1999, Kaufman et al. 2000, Antos and Parish 2002, Daniels 2003, MacKinnon 2003, North et al. 2004, Zenner 2005), although not universally (e.g., Larson and Franklin 2006). Tree mortality rates have a “reversed-J” dependence on tree-size or are independent of tree size (Harcombe 1987, Franklin and Debell 1988, Lorimer et al. 2001). Thus, in many situations, most of the physically smaller pieces of LWD entering the channel will originate from small trees near the channel. In uniform-height stands, such as plantations or early-successional forests following a stand-initiating disturbance, larger trees may be relatively more abundant (He and Duncan 2000) and a greater proportion of the small LWD will originate further from the channel.

Because the stability of a LWD piece depends on its size relative to channel dimensions, the biasing effects of fluvial displacement on the observed source distance distribution will vary with channel size. In very small channels, pieces of wood that are classified as LWD will be large relative to channel dimensions, few pieces will be displaced, and observed source distances will reflect the true cumulative distribution of piece origins. As channel size increases, increasingly larger pieces of LWD can be displaced and become unidentifiable as to origin. If the smaller, more-readily transported pieces disproportionately originate from the near-channel portion of the source distance curve, as argued above, the observed cumulative distribution of source distances will underestimate the proportion of pieces from near channel sites, and source distances will be overestimated for much of the cumulative distribution. As channel size continues to increase, the unmoved LWD will increasingly reflect the lateral distribution of the largest pieces. Because the piece size contributed by a tree of a given height decreases with distance from the channel, the observed cumulative distribution of piece origins will shift towards that of the larger trees, and finally to that of large trees originating near the channel; the observed cumulative distributions of origins will eventually underestimate the true distribution over much of its range. Thus, in general, we expect LWD source distances to be accurate for small streams, to be overestimated for intermediate size streams, and to be underestimated for large streams. In all cases, the maximum distance from which LWD is recruited to the channel will be underestimated, at least for treefall inputs. LWD pieces that have been displaced from their entry points are not necessarily omitted from direct surveys, however, because the fall direction and dimensions of partial logs or stumps in areas adjoining the channel may allow the entry and approximate dimensions of missing wood to be inferred.

While we are aware of the potential biases in the available field data, we cannot assess whether they would distort our overall conclusions. Direct monitoring of LWD inputs over time at reference sites might reduce the potential biases inherent in synoptic surveys.

Management implications

Our analyses have several implications for the management of LWD recruitment by means of riparian buffers. First, the analysis supports the practice of varying mandatory buffer widths according to site characteristics (Lee et al. 2004) such as tree height, and suggests additional characteristics (channel type and width, LWD delivery mechanism) that might be used. It also suggests potential modifications to existing regulations, although one must recognize the limitations of the current data and the multiple purposes served by riparian buffers. While our analyses for volume inputs largely agree with the BC Riparian Area Regulations (Table 1) for riffle-pool channels where 18 of 21 data points fell within the "zone of sensitivity" defined by the regulations (Fig. 5), the regulations performed less well for step-pool channels where only 8 of 19 data points fell within the designated zone of sensitivity, and they performed quite poorly for cascade-pool channels, where only 1 of 7 data points fell within the zone of sensitivity. This discrepancy is partly due to land slides being a common LWD delivery mechanism in the available data, but the result also seems to hold where bank erosion was identified as the dominant LWD input process. The RAR zones of sensitivity generally did not encompass source distances for numbers of LWD pieces in these data sets (Fig. 5). The RAR designation of a "zone of sensitivity" for LWD recruitment uses a procedure separate from the regulations in Table 1 to include unstable slopes from which land

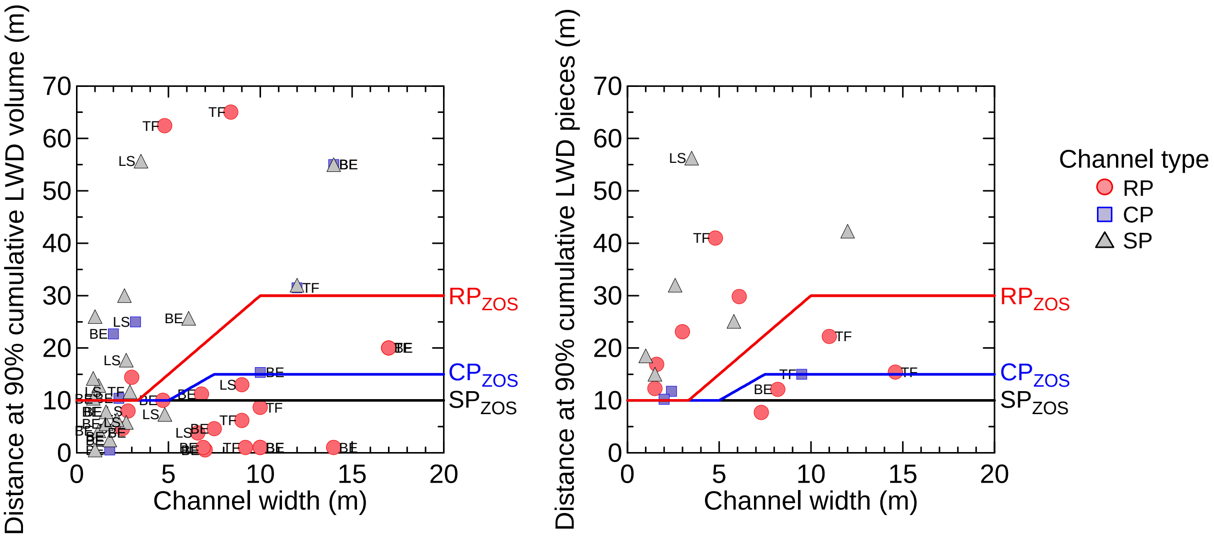

Figure 5. Effects of channel width, channel type, and dominant delivery mechanism on the source distance within which 90% of the volume (left panel) and number (right panel) of large woody debris (LWD) pieces originate. Channel types are riffle-pool (RP), cascade-pool (CP), and step-pool (SP). LWD delivery mechanisms are bank erosion (BE), land slides (LS), and tree fall (TF). Lines indicate the "zone of sensitivity" defined for different channel types and widths under the BC Riparian Area Regulations (see Table 1 for details).

slides might introduce LWD to a stream, so Fig. 5 likely over-estimates discrepancies with empirical data. Moreover, because many published LWD source distance curves are from research studies on particular types of streams rather than from random surveys, they are unlikely to reflect the true frequency of delivery mechanisms across the landscape.

Second, the quantile plots of the distributions of source distances at which specified proportions of cumulative LWD inputs were attained (Fig. 2) allow resource managers to better link management actions to the probability of attaining management goals. Consequently, risk can be included explicitly in the determination of buffer widths, for example, by using the 75th quantile rather than a mean or median source distance. Third, because LWD delivery mechanism can be an important modifier of LWD source distance, circumstances where an input mechanism cannot operate normally may require special management consideration. For example, normal rates of bank erosion along alluvial channels in urban settings may be deliberately reduced by management actions required to protect public safety. Maintaining near normal LWD inputs in such circumstances may require active management of LWD or buffer widths that differ from those that would otherwise suffice.

Only three of the 137 LWD source distance curves available for this analysis were for BC sites. While the qualitative forms of relationships among LWD source distances and predictor variables such as tree height, channel type, and channel width may be correctly represented in our analyses, quantitative results should be applied to BC streams with caution. It would be very desirable to obtain additional data from streams within the areas to which the results of this analysis are intended to apply.

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References

Abbe, T.B., and Montgomery, D.R. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers: Research and Management 12: 201-221.

Abbe, T.B., and Montgomery, D.R. 2003. Patterns and processes of wood debris accumulation in the Queets river basin, Washington. Geomorphology 51:81-107.

Acker, S.A., Gregory, S.V., Lienkaemper, G., McKee, W.A., Swanson, F.J., and Miller, S.D. 2003. Composition, complexity, and tree mortality in riparian forests in the central Western Cascades of Oregon. Forest Ecology and Management 173: 293-308.

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

Anonymous. 1996. Channel assessment procedure field guidebook. Forest Practices Code of British Columbia. BC Ministry of Forests, Victoria.

Antos, J.A., and Parish, R. 2002. Dynamics of an old-growth, fire-initiated, subalpine forest in southern interior British Columbia: tree size, age, and spatial structure. Canadian Journal of Forest Research 32: 1935-1946.

Beechie, T.J., and Sibley, T.H. 1997. Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams. Transactions of the American Fisheries Society 126: 217-229.

Beechie, T.J., Liermann, M., Pollock, M.M., Baker, S., and Davies, J. 2006. Channel pattern and river-floodplain dynamics in forested mountain river systems. Geomorphology 78: 124-141.

Benda, L.E., Bigelow, P., and Worsley, T.M. 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, U.S.A. Canadian Journal of Forest Research 32: 1460-1477.

Benda, L., Miller, D., Sias, J., Martin, D., Bilby, R., Veldhuisen, C., and Dunne, T. 2003. Wood recruitment processes and wood budgeting. Pp. 49-73. *In* The ecology and management of wood in world rivers. *Edited by* Gregory, S.V., Boyer, K.L., and Gurnell, A.M. Symposium 37, American Fisheries Society, Bethesda, Maryland.

Berg, N., Carlson, A., and Azuma, D. 1998. Function and dynamics of woody debris in stream reaches in the central Sierra Nevada, California. Canadian Journal of Fisheries and Aquatic Sciences 55: 1807-1820.

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

Bilby, R.E., and Likens, G.E. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61: 1107-1113.

Bilby, R.E., and Ward, J.W. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Transactions of the American Fisheries Society 118: 368-378.

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

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

Blinn, C.R., and Kilgore, M.A. 2004. Riparian management practices in the eastern U.S.: a summary of state timber harvesting guidelines. Water, Air, and Soil Pollution: Focus 4: 187-201.

Bocchiola, D., Rulli, M.C., and Russo, R. 2006a. Transport of large woody debris in the presence of obstacles. Geomorphology 76: 166-178.

Bocchiola, D., Rulli, M.C., and Russo, R. 2006b. Flume experiments on wood entrainment in rivers. Advances in Water Resources 29: 1182-1195.

Bragg, D.C. 2000. Simulating catastrophic and individualistic large woody debris recruitment for a small riparian system. Ecology 81: 1383-1394.

Braudrick, C.A., Grant, G.E., Ishikawa, Y., and Ikeda, H. 1997. Dynamics of wood transport in streams: a flume experiment. Earth Surface Processes and Landforms 22: 669-683.

Braudrick, C.A., and Grant, G.E. 2000. When do logs move in streams? Water Resources Research 36: 571-583.

Buffington, J.M., and Montgomery, D.R. 1999. Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resources Research 35: 3507-3521.

Buffington, J.M., Lisle, T.E., Woodsmith, R.D., and Hilton, S. 2002. Controls on the grain size and occurrence of pools in coarse-grained forest rivers. River Research and Applications 18: 507-531.

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

Church, M. 1992. Channel morphology and typology. Pp. 126-143 *In* The rivers handbook. *Edited by* P. Callow and G.E. Petts. Blackwell Scientific Publications, Oxford.

Collier, K.J., and Halliday, J.N. 2000. Macroinvertebrate-wood associations during decay of plantation pine in New Zealand pumice-bed streams: stable habitat or trophic subsidy? Journal of the North American Benthological Society 19: 94-111.

Dahlström, N., and Nilsson, C. 2006. The dynamics of coarse woody debris in boreal Swedish forests are similar between stream channels and adjacent riparian forests. Canadian Journal of Forest Research 36: 1139-1148.

Daniels, L.D. 2003. Western redcedar population dynamics in old-growth forests: contrasting ecological paradigms using tree rings. Forestry Chronicle 79: 517-530.

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

Faustini, J.M., and Jones, J.A. 2003. Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. Geomorphology 51: 187-205.

Fischer, R.A., and Fischenich, J.C. 2000. Design recommendations for riparian corridors and vegetated buffer strips. EMRRP Technical Note Series ERDC TN-EMRRP-SR-24, U.S. Army Engineer Research and Development Center, Vicksburg.

Fox, M., and Bolton, S. 2007. A regional and geomorphic reference for quantities and volumes of instream wood in unmanaged forested basins of Washington State. North American Journal of Fisheries Management 27: 342-359.

Franklin, J.F., and Debell, D.S. 1988. Thirty-six years of tree population change in an old-growth *Pseudotsuga-Tsuga* forest. Canadian Journal of Forest Research 18: 633-639.

Grizzel, J., McGowan, M., Smith, D., and Beechie, T. 2000. Streamside buffers and large woody debris recruitment: evaluating the effectiveness of watershed analysis prescriptions in the North Cascades region. Washington Department of Ecology, Timber/Fish/Wildlife Effectiveness Monitoring Report TFW-MAGI-00-003.

Gurnell, A.M., Piégay, H., Swanson, F.J., and Gregory, S.V. 2002. Large wood and fluvial processes. Freshwater Biology 47: 601-619.

Harcombe, P.A. 1987. Tree life tables. BioScience 37: 557-568.

Halwas, K.L., and Church, M. 2002. Channel units in small, high gradient streams on Vancouver Island, British Columbia. Geomorphology 43: 243-256.

Haga, H., Kumagai, T., Otsuki, K., and Ogawa, S. 2002. Transport and retention of coarse woody debris in mountain streams: an in situ field experiment of log transport and a field survey of coarse woody debris distribution. Water Resources Research 38(8): 1.1-1.16.

Hassan, M.A., Hogan, D.L., Bird, S.A., May, C.L., Gomi, T., and Campbell, D. 2005. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. Journal of the American Water Resources Association 41: 899-919.

He, F., and Duncan, R.P. 2000. Density-dependent effects on tree survival in an old-growth Douglas fir forest. Journal of Ecology 88: 676-688.

Hilderbrand, R.H., Lemly, A.D., Dolloff, C.A., and Harpster, K.L. 1997. Effects of large woody debris placement on stream channels and benthic macroinvertebrates. Canadian Journal of Fisheries and Aquatic Sciences 54: 931-939.

Hilderbrand, R.H., Lemly, A.D., Dolloff, C.A., and Harpster, K.L. 1998. Design considerations for large woody debris placement in stream enhancement projects. North American Journal of Fisheries Management 18: 161-167.

Hogan, D.L. 1986. Channel morphology of unlogged, logged, and debris torrented streams in the Queen Charlotte Islands. BC Ministry of Forests, Land Management Report No. 49. Pp. 94.

Hogan, D.L., Bird, S.A., and Hassan, M.A. 1998. Spatial and temporal evolution of small coastal gravel-bed streams: influence of forest management on channel morphology and fish habitats. Pp. 365-392 *In* Gravel-bed rivers in the environment. *Edited by* P.C. Klingeman, R.L. Beschta, P.D. Komar, and J.B. Bradley. Water Resources Publications LLC, Highland Ranch, Colorado.

House, R.A., and Boehne, P.L. 1986. Effects of instream structures on salmonid habitat and populations in Tobe Creek, Oregon. North American Journal of Fisheries Management 6: 38-46.

Jackson, C.R., and Sturm, C.A. 2002. Woody debris and channel morphology in first- and second-order forested channels in Washington's coast ranges. Water Resources Research 38: 16-1 – 16-14.

Kaufmann, M.R., Regan, C.M., and Brown, P.M. 2000. Heterogeneity in ponderosa pine/Douglas-fir forests: age and size structure in unlogged and logged landscapes of central Colorado. Canadian Journal of Forest Research 30: 698-711.

Keller, E.A., and Swanson, F.J. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4: 361-380.

Kreutzweiser, D.P., Good, K.P., and Sutton, T.M. 2005. Large woody debris characteristics and contributions to pool formation in forest streams of the Boreal Shield. Canadian Journal of Forest Research 35: 1213-1223.

Larson, J.A., and Franklin, F.J. 2006. Structural segregation and scales of spatial dependency in *Abies amabilis* forests. Journal of Vegetation Science 17: 489-498.

Lee Benda and Associates, Inc. 2004. Wood recruitment to streams. Campbell Timberland Management, Fort Bragg, California. Available at: http://www.fire.ca.gov/cdfbofdb/pdfs/WoodRecrutSreamsFinal.pdf

Lee, P., Smyth, C., and Boutin, S. 2004. Quantitative review of riparian buffer width guidelines from Canada and the United States. Journal of Environmental Management 70: 165-180.

LePage, P. 1995. The size and age structure of mature, mixed-species forest stands in the ICH zone. BC Ministry of Forests, Prince Rupert Forest Region, Extension Note 12: 3 pp.

Lienkaemper, G.W., and Swanson, F.J. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. Canadian Journal of Forest Research 17: 150-156.

Likens, G.E., and Bilby, R.E. 1982. Development, maintenance, and role of organic-debris dams in New England streams. Pp. 122-128 *In* Sediment budgets and routing in forested drainage basins. *Edited by* F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanston. US Forest Service PNW-GTR-141.

Lorimer, C.G., Dahir, S.E., and Nordheim, E.V. 2001. Tree mortality rates and longevity in mature and old-growth hemlock-hardwood forests. Journal of Ecology 89: 960-971.

MacKinnon, A. 2003. West coast, temperate, old-growth forests. Forestry Chronicle 79: 475-484.

Martin, D.J., Robinson, M.E., and Grotefendt, R.A. 1998. The effectiveness of riparian buffer zones for protection of salmonid habitat in Alaska coastal streams. Unpublished report. Sealaska Corporation and Alaska Forest Association, Juneau, Alaska.

Martin, D.J. 2001. The influence of geomorphic factors and geographic region on large woody debris loading and fish habitat in Alaska coastal streams. North American Journal of Fisheries Management 21: 429-440.

Martin, D.J., and Benda, L.E. 2001. Patterns of instream wood recruitment and transport at the watershed scale. Transactions of the American Fisheries Society 130: 940-958.

May, C.L., and Gresswell, R.E. 2003. Large woody debris recruitment and redistribution in headwater streams in the southern Oregon Coast Range, U.S.A. Canadian Journal of Forest Research 33: 1352-1362.

McDade, M.H. 1987. The source area for coarse woody debris in small streams in western Oregon and Washington. M.Sc. thesis, Oregon State University, Corvallis. Data available at: http://www.fsl.orst.edu/lter/data/abstract.cfm?dbcode=TD010&topnav=97

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

McKinley, M. 1997. Large woody debris source distances for western Washington Cascade streams. Unpublished senior research project. University of Washington, College of Forest Resources, Seattle. Summary data given in: www.dnr.wa.gov/htdocs/agency/federalassurances/final_fphcp/14ch4d.pdf

Megahan, W.F. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho batholith. Pp. 114-121 *In* Sediment budgets and routing in forested drainage basins. *Edited by* F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanston. USDA Forest Service PNW-GTR-141.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M., and Pess, G. 1995. Pool spacing in forest channels. Water Resources Research 31: 1097-1105.

Montgomery, D.R., Abbe, T.B., Buffington, J.M., Peterson, N.P., Schmidt, K.M., and Smock, J.D. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. Nature 381: 587-589.

Montgomery, D.R., and Buffington, J.M. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109: 596-611.

Montgomery, D.R., Collins, B.D., Buffington, J.M., and Abbe, T.B. 2003. Geomorphic effects of wood in rivers. Pp. 21-47 *In* The ecology and management of wood in world rivers. *Edited by* S.V. Gregory, K.L. Boyer, and A.M. Gurnell. Symposium 37. American Fisheries Society, Bethesda, Maryland.

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

Nakamura, F., and Swanson, F.J. 1994. Distribution of coarse woody debris in a mountain stream, western Cascade Range, Oregon. Canadian Journal of Forest Research 24: 2395-2403.

Napolitano, M.B. 1998. Persistence of historical logging impacts on channel form in mainstem North Fork Caspar Creek. USDA Forest Service, General Technical Report PSW-GTR-168: 97-102.

North, M., Chen, J., Oakley, B., Song, B., Rudnicki, M., Gray, A., and Innes, J. 2004. Forest stand structure and pattern of old-growth western hemlock/Douglas fir and mixed-conifer forests. Forest Science 50: 299-311.

Opperman, J.J. 2002. Anadromous fish habitat in Cailifornia's Mediterranean-climate watersheds: influences of riparian vegetation, instream large woody debris, and watershed-scale land use. PhD Dissertation, University of California, Berkeley.

Pacific Lumber Company. 2003. Freshwater Creek Watershed Analysis, Appendix E: stream channel assessment. Available at: http://www.krisweb.com/biblio/hum_palco_wpn_2003_appendfwwa.pdf

Palik, B., Golladay, S.W., Goebel, P.C., and Taylor, B.W. 1998. Geomorphic variation in riparian tree mortality and stream coarse woody debris recruitment from record flooding in a coastal plain stream. Ecoscience 5: 551-560.

Parish, R., Antos, J.A., and Fortin, M.-J. 1999. Stand development in an old-growth subalpine forest in southern interior British Columbia. Canadian Journal of Forest Research 29: 1347-1356.

Reeves, G.H., Burnett, K.M., and McGarry, E.V. 2003. Sources of large wood in the main stem of a fourth-order watershed in coastal Oregon. Canadian Journal of Forest Research 33: 1363-1370.

Reid, L.M., and Hilton, S. 1998. Buffering the buffer. USDA Forest Service, General Technical Report PSW-GTR-168: 71-80.

Rex, J.F., Beaudry, L., and MacIsaac, E.A. 2006. Riparian restoration in MPB affected areas: hydrological considerations. Unpublished data. BC Ministry of Forests, 5th floor - 1011 4th Avenue, Prince George, B.C., V2L 3H9.

Roni, P., and Quinn, T.P. 2001. Density and size of juvenile salmonids in response to placement of large woody debris in western Oregon and Washington streams. Canadian Journal of Fisheries and Aquatic Sciences 58: 282-292.

Roni, P., Beechie, T.J., Bilby, R.E., Leonetti, F.E., Pollock, M.M., and Pess, G.R. 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. North American Journal of Fisheries Management 22: 1-20.

Shirvell, C.S. 1990. Role of instream rootwads as juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*O. mykiss*) cover habitat under varying streamflows. Canadian Journal of Fisheries and Aquatic Sciences 47: 852-861.

Sinsabaugh, R.L., Golladay, S.W., and Linkins, A.E. 1991. Comparison of epilithic and epixylic biofilm development in a boreal river. Freshwater Biology 25: 179-187.

Smock, L.A., Metzler, G.M., and Gladden, J.E. 1989. Role of debris jams in the structure and functioning of low-gradient headwater streams. Ecology 70: 764-775.

Sobota, D.J., Gregory, S.V., and Van Sickle, J. 2006. Riparian tree fall directionality and modeling large wood recruitment to streams. Canadian Journal of Forest Research 36: 1243-1254.

Swanson, F.J., and Lienkaemper, G.W. 1978. Physical consequences of large organic debris in Pacific Northwest streams. USDA Forest Service General Technical Report PNW-69.

Swanston, D.N., and Howes, D.E. 1991. Slope movement processes and characteristics. Pp. 1-17 *In* A guide for management of landslide-prone terrain in the Pacific Northwest. *Edited by* S.C. Chatwin, D.E. Howes, J.W. Schwab, and D.N. Swanston. BC Ministry of Forests, Land Management Handbook No. 18, Victoria, B.C.

Sweka, J.A., and Hartman, K.J. 2006. Effects of woody debris addition on stream habitat and brook trout populations in Appalachian streams. Hydrobiologia 559: 363-378.

Valett, H.M., Crenshaw, C.L., and Wagner, P.F. 2002. Stream nutrient uptake, forest succession, and biogeochemical theory. Ecology 83: 2888-2901.

Van Sickle, J., and Gregory, S.V. 1990. Modeling inputs of large woody debris to streams from falling trees. Canadian Journal of Forest Research 20: 1593-1601.

Wallace, J.B., Webster, J.R., and Meyer, J.L. 1995. Influence of log additions on physical and biotic characteristics of a mountain stream. Canadian Journal of Fisheries and Aquatic Sciences 52: 2120-2137.

Ward, G.M., and Aumen, N.G. 1986. Woody debris as a source of fine particulate organic matter in coniferous forest stream ecosystems. Canadian Journal of fisheries and Aquatic Sciences 43: 1635-1642.

Warren, D.R., and Kraft, C.E. 2003. Brook trout (*Salvelinus fontinalis*) response to wood removal from high-gradient streams of the Adirondack Mountains (N.Y., U.S.A.). Canadian Journal of Fisheries and Aquatic Sciences 60: 379-389.

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

Young, K.A. 2000. Riparian zone management in the Pacific Northwest: who's cutting what? Environmental Management 26: 131-144.

Zener, E.K. 2005. Development of tree size distributions in Douglas-fir forests under differing disturbance regimes. Ecological Applications 15: 701-714.

Appendix 1. Large woody debris definitions, input processes, stream reach, and riparian vegetation characteristics for studies reporting large woody debris source distance curves.

			LWD delivery (%)[d]				Channel		
ID code[a]	LWD definition[b]	% Sourced[c]	BE	TM	WT	LS	Width[e] (m)	Slope (%)	Tree height (m)
MK[f]	3 m x 0.1 m		52	14	34	0	8.2	1.0	30[g]
			24	27	48	1	11.0	2.0	30
			30	27	34	9	9.5	2.9	30
			54	15	31	0	20.3	0.8	30
			14	33	39	14	14.6	1.0	30
			60	20	20	0	31.4	0.4	30
McD	1 m x 0.1 m	52					1.0[h]	37.5[h]	58[i]
							2.6	24.2	58
							3.0	2.4	48[i]
							12.0	12.2	58
McK	NR[j]								
RH							5.3[k]	2.0	55
MRG	2 m x 0.1 m						15.8	2.6	17[m]
							18.4	0.8	17
							10.8	2.2	17
							7.5	4.1	17
							11.2	1.5	17
							4.4	3.7	17
							15.8	2.6	18[m]
							14.3	1.4	18
							14.1	2.6	18
							5.6	2.3	18
							14.4	2.8	18
							13.0	3.6	18
							7.2	1.5	18

Appendix 1. Continued.

			LWD delivery (%)				Channel		
ID code	LWD definition	% Sourced	BE	TM	WT	LS	Width (m)	Slope (%)	Tree height (m)
							4.9	1.7	18
							10.5	1.9	13[m]
							12.3	2.6	13
							14.0	1.0	13
							7.3	3.5	13
							7.6	2.8	13
							4.6	2.4	13
GMSB	2 m x 0.1 m						2.1 - 6.4	5.7 - 22.6	
							5.8[m]	7.0[m]	
							6.1	2.7	
BBW	1.8 m x 0.08 m (midpoint)	27	50[n]	18	0	32	14.0	5.9	65[p]
			100	0	0	0	14.0	4.0	65
			33	70	0	0	17.0	1.0	65
			27	73	0	0	17.0	1.0	65
			85	17	0	0	17.0	1.0	65
			5	95	0	0	9.0	1.0	25[p]
			71	25	0	0	10.0	1.0	25
			25	75	0	0	9.2	1.0	25
			16	83	0	0	10.0	1.5	25
			47	41	0	12	6.9	2.8	25
			74	26	0	0	10.0	1.8	25
			6	52	0	42	8.4	2.4	25
			100	1	0	0	8.0	2.1	25
			74	26	0	0	14.0	1.2	25
			0	73	0	27	12.0	4.0	25
			88	5	0	7	10.0	2.8	25
			41	5	0	52	4.8	10.0	25
			42	23	0	35	6.1	9.0	25
			61	43	0	0	2.2	41.0	25
			14	16	0	71	2.7	26.0	25
			13	88	0	0	2.9	20.0	25

Appendix 1. Continued.

			LWD delivery (%)				Channel		
ID code	LWD definition	% Sourced	BE	TM	WT	LS	Width (m)	Slope (%)	Tree height (m)
Opp	1 m x 0.1 m	16	34[q]	27	0	8	7.3[r]		
MG	2 m x 0.2 m	64	3	5	36	52	3.5[s]	17.7	60[t]
		78	7	5	73	10	4.8	3.0	60
PLC	1.8 m x 0.15 m	11	30	1	52	14[u]	9.7[v]		36
LBA		26[w]	81[w]	11	0	8	7.0	1.0	24[v]
							4.7	1.0	24
							2.5	2.0	24
							1.8	7.0	24
							1.2	8.0	24
							1.8	5.0	24
							1.0	9.0	24
		56[w]	35[w]	12	0	54	9.0	1.5	24
							6.6	1.3	24
							2.7	7.2	24
							2.8	1.6	24
							3.2	5.3	24
							0.9	8.3	24
		66[w]	46[w]	37	0	17	6.8	1.5	24
							7.5	2.2	24
							2.0	4.1	24
							1.6	8.8	24
							2.3	4.1	24
							1.6	10.4	24
							1.2	7.0	24
							0.9	10.2	24
BRM							1.5	2.0	23
							1.5	10.0	30
							1.6	4.0	30

Appendix 1. Continued.

			LWD delivery (%)				Channel		
ID code	LWD definition	% Sourced	BE	TM	WT	LS	Width (m)	Slope (%)	Tree height (m)
DN	0.5 m x 0.05						2.4[x] 2.0	5.2 5.9	

[a] Refer to Table 2 for codes to the studies.

[b] Piece length and basal diameter that were used to identify functional large woody debris.

[c] Proportion of functional large woody debris pieces for which a source distance was determined

[d] Percentage of LWD pieces or volume delivered by particular input processes: BE = bank erosion, TM = tree mortality, WT = windthrow, LS = landslides. Note that often a delivery process could not be identified for many LWD pieces.

[e] Mean bankfull width of the stream channel at the reach.

[f] Data for this study are reported as averages for multiple sites within channel types.

[g] Tree height data for Murphy and Koski (1989) are given in Reid and Hilton (1998).

[h] Bankfull channel width and channel slope data are given for 4 of 39 reaches.

[i] Mean values for multiple sites, reported separately for old-growth and second-growth riparian forest sites.

[j] Not reported. Blank cells in the table also indicate NR.

[k] Channel data from Napolitano (1998), USDA Forest Service Report PSW-GTR-168: 97.

[m] Median values, reported separately for groups of streams with different buffer widths.

[n] Percent volume.

[p] Mean tree heights, reported separately for all old-growth and all second-growth sites.

[q] The tree mortality excludes 12% inputs by branch breakage. An addition 17% entered by trees growing into the channel.

[r] Mean value for all surveyed sites (stream width data from J.J. Opperman (2005), Environmental Management 35: 266-277).

[s] Mean value for three second-order sites.

[t] Midpoint of range (50 – 70 m).

[u] Mass wasting induced by bank erosion.

[v] Mean value for all sites.

[w] Mean value from multiple sites within different drainages.

[x] Mean value for multiple sites, reported separately for old-growth and managed sites.

Appendix 2. Availability of large woody debris (LWD) source distance data by tree height, channel type, and channel width categories. Counts are the number of sites with complete information on tree height, channel width, and channel type.

Number of LWD pieces:

	Tree height category[a]			
	TH < 40 m		TH ≥ 40 m	
	Channel type[b]		Channel type	
Channel width class[c]	CP + SP	RP	CP + SP	RP
S	3	2	2	1
M	1	1	1	1
L	0	4	1	0

Volume of LWD:

	Tree height category			
	TH < 40 m		TH ≥ 40 m	
	Channel type		Channel type	
Channel width class	CP + SP	RP	CP + SP	RP
S	16	2	2	1
M	2	10	1	1
L	2	4	3	3

---

[a] Tree height and channel width categories are used here to summarize the availability of complete sets of data. ANCOVAs used measured tree height and channel width as continuous variables.

[b] Channel types are: RP = riffle-pool, CP = cascade pool, and SP = step-pool. CP + SP combines data for the “steep-gradient” CP and SP channel types.

[c] Channel width classes are: S = bankfull width ≤ 3.33 m, M = 3.33 m > width < 10 m, and L = width ≥ 10 m.

Appendix 3. Univariate relationships between large woody debris source distances and tree height.

Relative few determinations of LWD source distances provided complete information on channel type, channel size, riparian tree height, and LWD delivery mechanisms, but many studies reported tree height. Although these studies may confound the effects of unreported factors with tree height, sample sizes for assessing the effects of tree height are greatly increased. We summarize here the univariate response of LWD source distance to tree height. Note that several studies reported LWD source distance curves separately by stream reach, but gave tree height only as a mean value over all sites. We have assigned the same mean tree height to all sites in such cases. We assessed the relationship using linear regression. Source distances for numbers of pieces were log-transformed to improve homogeneity of variances, while those for LWD volume did not require transformation.

The relationships between the tree height and the distance within which 90% of the cumulative number or volume of LWD pieces originated are shown in Fig. A1. Source distances at a given tree height were quite variable, those for LWD volume inputs spanning a range of about 20 m, and those for number of LWD pieces spanning ranges of 10-25 m (Fig. A1). Nevertheless, source distances for both volume and numbers of LWD pieces increased with increasing tree height (Tables A1 and A2).

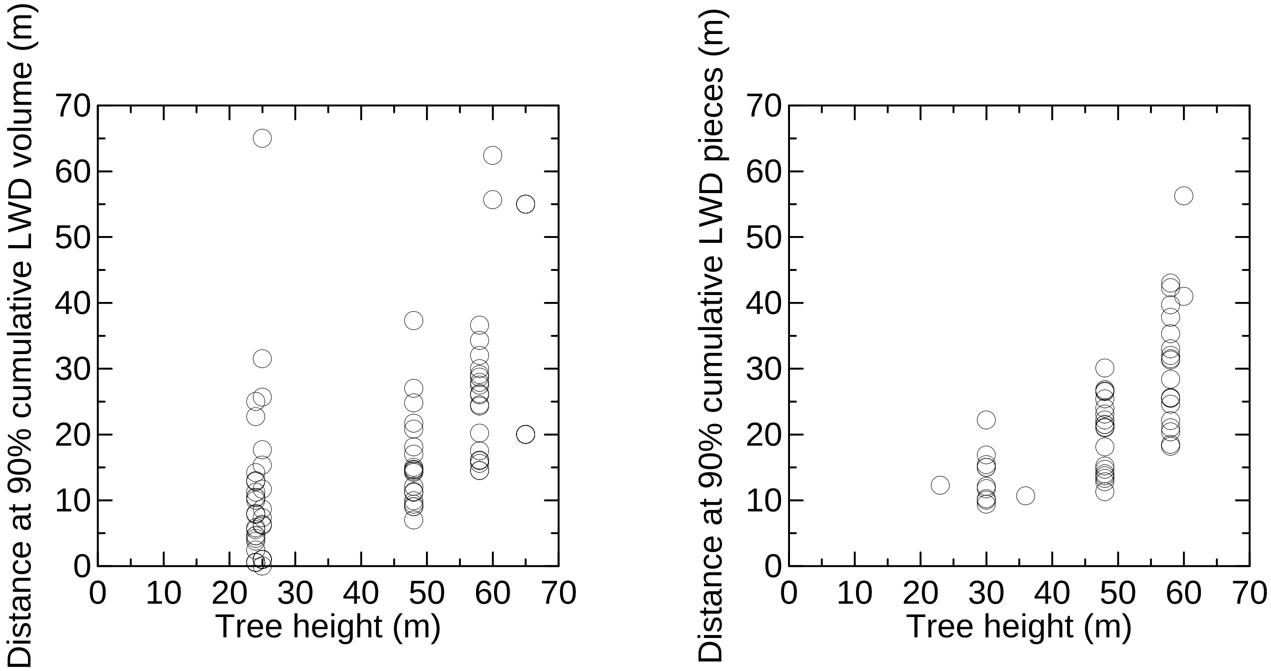

Figure A1. The lateral distance from the stream channel edge within which 90% of the cumulative volume (left panel, N = 83) or numbers (right panel, N = 53) of large woody debris pieces originated, as a function of the reported tree height of the riparian forest. Where tree height was reported as a mean for many sites, all sites have been assigned the same value.

Table A1. Effect of tree height (m) on the distance (m) within which 90% of the cumulative volume of large woody debris pieces originated. $R^2 = 0.29$ ($N = 83$) for the linear regression model:

$$\text{Source distance} = \text{Constant} + \text{Tree height}$$

Factor	Coefficient	SE	*t*	*P*
Constant	-2.932	3.672	-0.798	0.427
Tree height[a]	0.495	0.083	5.932	< 0.001

[a] Mean tree height in m (continuous variable).

Table A2. Effect of tree height (m) on the distance (m) within which 90% of the cumulative number of large woody debris pieces originated. $R^2 = 0.53$ ($N = 53$) for the regression model:

$$\log_{10}(\text{Source distance}^{a}) = \text{Constant} + \text{Tree height}$$

Factor	Coefficient	SE	*t*	*P*
Constant	0.7180	0.0805	8.918	< 0.001
Tree height[b]	0.0126	0.0016	7.683	< 0.001

[a] Source distances were $\log_{10}$-transformed to ensure homogeneity of variances.

[b] Mean tree height in m (continuous variable).