Source distances for coarse woody debris entering small streams in western Oregon and Washington[1]

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Received September 13, 1988

Accepted September 26, 1989

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. Can. J. For. Res. **20**: 326–330.

Coarse woody debris from streamside forests plays important biological and physical roles in stream ecosystems. The distance from stream bank to rooting site was determined for at least 30 fallen trees at each study site on 39 streams in the Cascade and Coast ranges of Oregon and Washington. The study sites varied in channel size (first- through third-order), side-slope steepness (3 to 40°), and age of surrounding forest (mature or old-growth stands). The distribution of distances from rooting site to bank was similar among streams, with 11% of the total number of debris pieces originating within 1 m of the channel and over 70% originating within 20 m. Stands with taller trees (old-growth conifers) contributed coarse woody debris to streams from greater distances than did stands with shorter (mature) trees.

65.62 ft

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Les bois morts dans les forêts qui longent les cours d'eau jouent un rôle important tant du point de vue physique que biologique dans l'écosystème de ces cours d'eau. La distance entre la rive et la zone d'enracinement a été mesurée pour au moins 30 arbres renversés à chacune des places d'étude le long de 39 cours d'eau des Cascades et des Coast ranges dans les états de l'Orégon et de Washington. Les places d'étude différaient par la largeur du cours d'eau (du premier au troisième ordre), l'inclinaison des pentes de chaque côté des cours d'eau (3 à 40°) et l'âge de la forêt environnante (forêts matures ou vieilles forêts). Les distances entre la rive et la zone d'enracinement avaient une distribution semblable pour tous les cours d'eau, avec 11% des bois morts situés en dedans de 1 m des cours d'eau et 70% en dedans de 20 m. Les sources de débris ligneux étaient plus éloignées dans les peuplements avec les arbres les plus hauts, soit les vieilles forêts de conifères que dans les peuplements matures avec des arbres plus courts.

[Traduit par la revue]

Introduction

Coarse woody debris in the form of large limbs, chunks of wood, and entire trees is widely recognized as a major element in the physical and biological structure of forested stream ecosystems (Swanson *et al.* 1976, 1982; Anderson *et al.* 1978; Bilby and Likens 1980; Triska and Cromack 1980; Harmon *et al.* 1986). A variety of mechanisms, windthrow, stream-bank erosion, landslides, and others, transfer coarse woody debris from forests to streams (Keller and Swanson 1979). Such debris is an important link between these two environments: it traps sediment to form new surfaces for colonization by plants (Swanson and Lienkaemper 1980), creates complex aquatic habitat (Triska and Cromack 1980), and may damage stream banks and riparian forests when transported during high flows.

The delivery rates (Lienkaemper and Swanson 1987) and sources of coarse woody debris in streams are important factors in characterizing forest–stream linkages. Information on source distance (the straight-line distance downslope to the stream bank from the rooting site of a plant producing coarse debris (Fig. 1)) is essential in defining the areal extent of the zone of this important forest–stream interaction. Where management activities, such as creation of narrow buffer strips, or natural processes limit the width of patches of streamside forest, the production of coarse woody debris may be affected.

The objective of this study was to determine the source-distance patterns of coarse woody debris in selected streams flowing through natural conifer forests in the Cascade and Coast mountains of western Oregon and Washington. Several stand and landform conditions were sampled to estimate their effects on source-distance patterns of stream-

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Printed in Canada / Imprimé au Canada

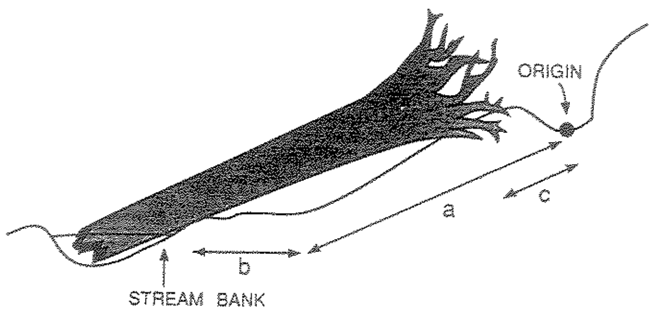

FIG. 1. Measurements of source distance from origin to stream bank ($a + b$) and origin to piece distance (c).

side forests. We sampled old-growth and mature forests containing conifers and hardwoods to provide data on a range of tree heights. Hillslope steepness was considered in the sampling because we expected that if debris slid down steep slopes, source distances would be greater at sites with steeper side slopes and narrower floodplains. Sampled sites included a range of stream orders from first to third (Strahler 1957) because floodplain width in this region generally increases with increasing stream order.

Study sites

The 39 study sites, 37 in the Cascade Range of Oregon and Washington and 2 in the Coast Range of Oregon, are located within 8 study areas (Fig. 2). Streams at the study sites range in size from first- through third-order; all of the sampled stream sites are in natural, well-stocked stands. Approximately half the sites are in old-growth (>200-year-old) stands, and half are in unmanaged, mature (80- to 200-year-old) stands. Legal descriptions of locations and other site characteristics are available in McDade (1987).

Twenty-seven of the Cascade Range streams are in the central western Cascades of Oregon, in the H.J. Andrews Experimental Forest or in the nearby Hagan Block and Middle Santiam research natural areas and Three Sisters Wilderness Area. Nine of the remaining Cascade streams are close to the Wind River Experimental Forest near Carson, Washington, and one is in Mount Rainier National Park. Forests bordering the streams are dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western red cedar (*Thuja plicata* Donn ex D. Don), which are characteristic of the *Tsuga heterophylla* Zone (Franklin and Dyrness 1973).

Streams sampled in the Oregon Coast Range are Calf Creek (Neskowin Crest Research Natural Area, Cascade Head Experimental Forest) and Flynn Creek (Flynn Creek Research Natural Area). Calf Creek, only 2.5 km from the Pacific Ocean, lies within the coastal *Picea sitchensis* Zone (Franklin and Dyrness 1973), with forests dominated by Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and western hemlock of about 140 years. Flynn Creek is located 16 km east of the Pacific Ocean in the *Tsuga heterophylla* Zone (Franklin and Dyrness 1973). Douglas-fir and western hemlock dominate the forest canopy. Red alder (*Alnus rubra* Bong.) is common along both streams.

Valleys in both the Cascade and Coast ranges are typically V-shaped with steep side slopes and narrow valley floors along first- through third-order streams. Hillslopes adjacent to sampled streams range in steepness from 3 to 40°, with first- and second-order streams having significantly steeper side slopes than third-order streams (Table 1).

Methods

The length of stream sampled at each site ranged from 0.4 to 2 km and was determined by the distance required to locate 30 trees (sources) that had provided pieces of coarse woody debris to the stream; minimum diameters were greater than 10 cm at the small

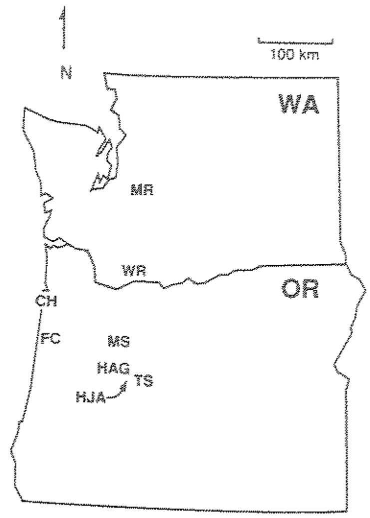

FIG. 2. Study areas in Oregon and Washington. MR, Mount Rainier National Park; WR, Wind River Experimental Forest; CH, Cascade Head Experimental Forest; FC, Flynn Creek Research Natural Area; MS, Middle Santiam Research Natural Area; HAG, Hagan Block Research Natural Area; TS, Three Sisters Wilderness Area; and HJA, H.J. Andrews Experimental Forest.

end and lengths were greater than 1 m. Coarse debris includes tree tops, large limbs, fragments of snags, and whole trees. Sample size (30) was a compromise between the need to properly characterize a site and to keep stream length short enough that geomorphic conditions (e.g., stream order, floodplain width) would not vary greatly. The origin of each piece of debris within or straddling the stream was determined. Pieces not identifiable as to source (47.7% of pieces encountered at the study sites) were not included in the study; they were usually short fragments that were quite mobile at high flows.

Source distance was measured from the origin to the stream bank along a line perpendicular to the channel. To evaluate the distance moved downslope by debris, we also measured the origin to piece distance (Fig. 1). Separate measurements were made of distances on bench and hillslope areas and then summed to give a total slope distance from origin to stream (source distance) or origin to piece, as appropriate. A bench was defined as the relatively flat floodplain and terraces adjacent to the stream. Side-slope steepness was measured with a hand-held clinometer.

Species, diameter, total piece length, and length actually in channel were recorded for pieces with discernible origins. In cases of uprooted trees, the distance from the center of the root pit to the stream bank was measured. In cases where a fallen tree delivered more than one piece of debris to the stream, all of these pieces were inventoried separately, but their source was counted as one. Debris pieces that straddled the stream but were identifiable as to source location were included in the study because they will eventually enter the stream.

Each study site was classified in terms of stream order (first, second, or third), stand age (old-growth or mature timber), and average steepness of side slopes (steep slopes > 25°, gentle slopes < 25°). These characteristics were pre-established so that selected sites would fit a 3 × 2 × 2 factorial design with a minimum of three sample sites (replicates) in each cell of the matrix. The choice of 25° for categorizing slope steepness was based on our field observations that conspicuous sliding occurs primarily on slopes steeper than 25–30°. A total of 1258 debris pieces were sampled: 619 conifer and 2 hardwood pieces in old-growth stands and 551 conifer and 86 hardwood pieces in mature stands.

Dependent variables (Table 1) had highly skewed distributions, and nonparametric methods were used throughout to test for location differences among distributions classified by various stand

TABLE 1. Median values of debris-related variables and slope steepness, according to slope class, stand–debris type, and stream order

	Side-slope class		Stand–debris type			Stream order		
	Steep ($N=630$)	Gentle ($N=626$)	Old-growth conifer ($N=619$)	Mature conifer ($N=551$)	Mature hardwood ($N=86$)	First ($N=423$)	Second ($N=450$)	Third ($N=383$)
Source distance, origin to stream (m)	10.0	9.2	10.4	9.8	3.6	9.7	9.3	11.0
Piece length (m)	15.0	20.7	20.7	15.9	11.4	16.9	16.6	20.0
Piece diameter (cm)	50.0	45.0	65.0	35.0	32.0	42.0	46.0	53.0
Side-slope steepness (degrees)	35.0	8.0	17.5	20.0	0.0	20.0	20.0	10.0
Origin to piece distance (m)								
For moved pieces only	7.0	4.6	7.0	5.0	5.1	5.2	5.6	5.7
Percentage of pieces that moved[a]	52	33	43	45	35	46	44	38

NOTE: Underlined values indicate that there was no significant difference ($p > 0.05$) in distribution locations (Wilcoxon test for two levels, Kruskal–Wallis test for three levels).
[a]Values are percentages, with significance evaluated by χ^2-test of independence.

(e.g., stand–debris type) and geomorphic (e.g., slope steepness) attributes.

Results and discussion

Debris piece size

Piece length and diameter were significantly less in mature than in old-growth stands, and in hardwoods than in conifers (Table 1), primarily because of differences in tree heights. Although there was some overlap in conifer heights between mature stands (40–65 m) and old-growth stands (50–80 m), the average height in the mature stands was smaller (48.0 vs. 57.6 m, based on samples from four sites).

In mature and old-growth riparian stands sampled in this study, hardwood trees are commonly shorter than conifers, for one of two reasons. First, hardwoods form nearly pure stands on sites immediately adjacent to streams that have been recently disturbed by fluvial processes. These hardwoods are, therefore, typically younger and shorter than neighboring mature or old-growth conifer stands. Second, when hardwood trees are of the same age and are intermixed with conifers of mature or old-growth age, the conifers have the biological potential to grow taller than the associated hardwoods and usually express that potential by 80–100 years.

Diameters of pieces from gentle slopes were significantly smaller than those of pieces from steep slopes (Table 1), a relation probably indicating that broad, flat valley floors contained a greater abundance of mature hardwoods and conifers than of old-growth trees. This greater abundance of mature trees in broad, flat valleys is possibly due to more frequent disturbance by flooding there than on steep-sided canyons with narrow floors. The frequent disturbance would produce a mix of stands with smaller trees at earlier successional stages.

On the other hand, the steep side slopes yielded significantly shorter pieces than did gentle ones, probably because of greater breakage in trees that fall across a steep-sided, V-shaped stream valley.

Piece length and diameter were significantly greater in third- than in first-order channels (Table 1). This pattern is consistent with the lower breakage one would expect from trees falling across wider, third-order channels and valley floors. Similarly, the lower breakage expected in higher order channels would lead to larger piece diameters there.

Downslope movement of debris

A significantly greater percentage of pieces moved toward the stream on steep slopes than gentle slopes, and the distance moved was also greater on steep slopes (Table 1). Old-growth pieces moved significantly farther than did pieces from mature stands, possibly because of the downhill lean more commonly observed in old-growth trees than in those of mature stands. Furthermore, there is greater potential for downslope sliding of the massive old-growth boles because of the greater momentum they achieve while falling. Old-growth also typically has fan-shaped systems of relatively small diameter limbs that would offer little resistance to sliding. Significantly fewer pieces moved in the hardwood than in the conifer components of mature stands, probably because of less steep slopes in areas where hardwood stands are common (Table 1). There was no significant association between downslope movement and stream order.

Source distance

Source distance was significantly less in mature than in old-growth conifers and least in mature hardwoods (Table 1). As with piece size, the differences can be attributed to different heights in the three types of trees. More than 83% of the hardwood pieces originated within 10 m of the stream channel, as compared with 53% of the conifer pieces; all hardwood pieces were delivered from within 25 m of the channel, but 13% of the conifer pieces had a source distance greater than 25 m.

There was no significant difference between source distances on steep and gentle side slopes (Table 1), even though the percentage of moving pieces and the distance moved were greater on the former.

There was no significant association between source distance and stream order (Table 1). Coupled with the similar result for downslope movement of debris, this lack of pattern suggests that stream order alone is a poor predictor of debris delivery.

Pooling all sites in the study revealed that more than 70% of the woody debris originated within 20 m of the channel

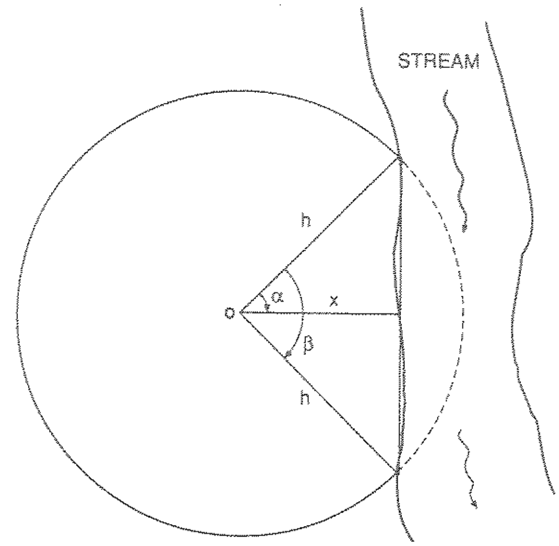

FIG. 3. Trigonometry used in modeling probability of a tree of height h at origin 0 and source distance x entering a stream. β is the angle formed by the intersection of two tree-length radii extending from the origin to the stream bank and α is 0.5β.

and 11% originated within 1 m of the bank. Maximum observed source distance was 60.5 m in an old-growth stand.

Of the 11% originating within 1 m of the bank, streambank erosion may have contributed to their delivery to the streams. The remaining 89% of the pieces were delivered to the stream by windthrow and other processes unrelated to bank erosion. The preponderance of debris from trees rooted away from the bank parallels the findings of Lienkaemper and Swanson (1987). In their study of debris entering first- through fifth-order streams inventoried annually over a 9-year period in the western Cascade Range, 34% of the total pieces originated within 1 m of the stream and delivery of the remaining 66% of the pieces was unrelated to bank erosion.

Several factors may account for the difference in percentage of pieces originating near stream banks in the two studies: (*i*) the period of time over which debris entered the streams sampled in the present study is much longer than the 9-year period of study by Lienkaemper and Swanson (1987), and erosion may have removed evidence of bankside origin, biasing the sample toward origins farther from the stream (the greater sampling frequency of Lienkaemper and Swanson (1987) over their 9-year study would have identified the bankside origin); (*ii*) Lienkaemper and Swanson (1987) sampled large channels, including a fifth-order site, where debris resulting from bank erosion may be more common and where exposure to wind may be greater; and (*iii*) susceptibility of the sampled sites to erosion probably varied in the two studies because of differences in channel slope, geomorphology of the valley floor, texture of bank materials, and other factors. Factors *i* and *ii* probably accounted for the lower levels of debris deposits triggered by bank erosion in this study. Factor *iii* had unknown effects on the relative importance of bank erosion in the two studies. It should be noted that even without recent bank erosion, trees rooted in the stream bank frequently lean over the stream and may eventually fall into the stream as a result of the asymmetry of their rooting and crown environments (Lienkaemper and Swanson 1987).

Modeling source distances

A simple trigonometric model based on the assumptions of uniform tree height, random direction of tree fall, and uniform stocking density can be used to represent a theoretical distribution of source distances for stands. This model is developed to provide a general representation of the relation between source distance and tree height; such a representation is needed because most forests have shorter trees than do those in our study area.

The probability (P_d) of a falling tree entering a stream is

$$P_d = \frac{\beta}{360}$$

where β is the angle formed by the intersection of two tree-length radii extending from the origin to the stream bank. This relation is depicted in Fig. 3, where α is defined as 0.5β, x is the source (perpendicular) distance from stream bank to origin, and h is tree height. From Fig. 3 it follows that

$$\cos \alpha = x/h$$

and that

$$P_d = \frac{2(\cos^{-1} x/h)}{360}$$

The probabilities, P_d, at source distances, x, can be used to estimate the probability that a randomly chosen debris piece in a stream originated from any specific source distance, assuming that all trees in a riparian stand are of the same height, h. Let x_j ($j = 1,2,\ldots$) delimit a sequence of equally wide intervals of distance away from the stream, with the common interval widths being small enough that P_d is nearly constant within each interval. If stocking density and tree fall rate are assumed constant with respect to distance from the stream, falling trees are equally likely to come from any interval x_j. With these assumptions Bayes' Rule from elementary probability theory (e.g., Breipohl 1970) shows that the probability, $P_s(x_j)$, of a piece in the stream originating from the interval x_j is given by

$$P_d(x_j) \Big/ \sum_j P_d(x_j)$$

This model was used to compute the probability distributions of source distances for $h = 40$ and 50 m, and the results were compared with the observed distributions of source distance (Fig. 4). Tree heights of 40 and 50 m were used as being representative for dominant trees in mature and old-growth stands. For the first 20 m from the stream bank, observed cumulative source-distance distributions for all three stand–debris types rose more rapidly than did the model curves (Fig. 4). This pattern was primarily due to the model assumptions of fixed-height stands of 40 or 50 m. Tree heights vary substantially in natural stands, particularly in old-growth forests. The rapid rise of the observed distribution for hardwoods was due to their short stature.

The discrepancy between model and observed source distances close to the stream may also have been due to higher stand densities near streams, or, even more likely, to higher mortality there. In areas close to the stream bank, high water tables and noncohesive soil may lead to erosion and high susceptibility to windthrow and therefore increase the probability of debris entering the stream.

Our research group is currently extending the model to mixed-height stands in which stand density and tree mortality may vary with source distance. However, even without

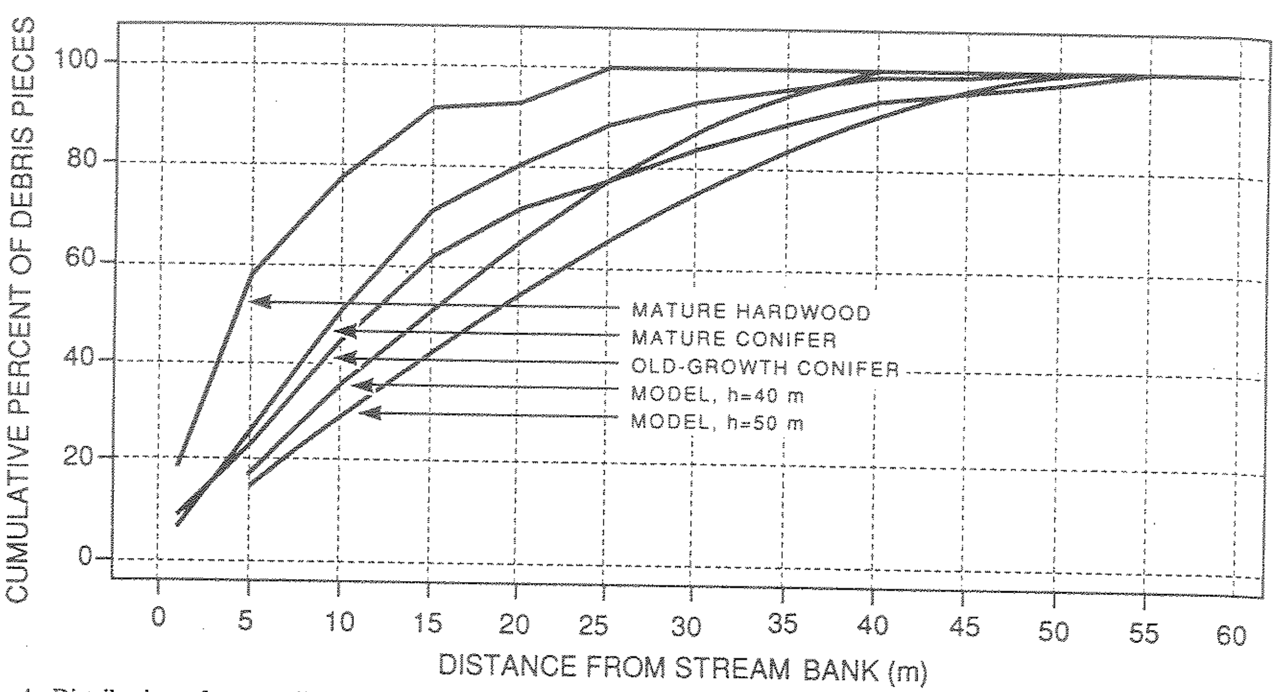

FIG. 4. Distribution of source distances from origin to stream bank for conifers in old-growth stands and hardwoods and conifers in mature stands (as based on field observations) and for trees 40 and 50 m tall (as calculated from a trigonometric model of debris delivery). See text for simplifying assumptions.

this flexibility, the model gives a reasonable approximation of the distribution of debris origins as a function of tree height.

Our results can be used to interpret the effects of buffer strips of various widths on future amounts of coarse woody debris entering streams. Composite data from sampled old-growth conifer forests, for example, indicate that a 30 m wide (horizontal distance) strip of streamside forest would produce 85% of the observed debris and that a strip of forest 10 m wide would supply less than 50% of this debris (Fig. 4). How buffer strips of these widths would actually perform as sources of coarse woody debris on various time scales depends on additional factors, such as the influence of windthrow after the adjacent stand has been removed (Steinblums *et al.* 1984). And of course, production of coarse debris is only one of the influences of forests on stream systems.

Acknowledgements

This work was supported in part by National Science Foundation grants BSR-8508356 and BSR-8514325 and by Research Work Unit PNW-4356 of the USDA Forest Service, Pacific Northwest Research Station. The authors thank G. Spycher (Oregon State University) for extensive help with quantitative analysis and L. Franklin (Oregon State University) for help in the field. Data used in this study are from McDade's (1987) thesis and are on file at the Forest Science Data Bank, Oregon State University.

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