Sources of large wood in the main stem of a fourth-order watershed in coastal Oregon[1]

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Abstract: We compared the contribution of large wood from different sources and wood distributions among channel zones of influence in a relatively pristine fourth-order watershed in the central Coast Range of Oregon. Wood in the main stem of Cummins Creek was identified as coming from either (*i*) streamside sources immediately adjacent to the channel or (*ii*) upslope sources delivered by landslides or debris flows more than 90 m from the channel. About 65% of the number of pieces and 46% of the estimated volume of wood were from upslope sources. Streamside sources contributed about 35% of the number of pieces and 54% of the estimated volume of wood. The estimated mean volume of upslope-derived pieces was about one-third that of streamside-derived pieces. Upslope-derived pieces were located primarily in the middle stream reaches and in the zones of influence that had the most contact with the low-flow channel. Streamside-derived pieces were more evenly distributed among the examined reaches and were predominately in the influence zones that had the least contact with the low-flow channel. Our findings suggest that previous studies that examined only streamside sources of wood have limited applications when designing and evaluating riparian management approaches in landslide-prone areas. The failure to recognize the potential sources of wood from upslope areas is a possible reason for the decline of large wood in streams in the Pacific Northwest.

Résumé : Nous avons comparé la contribution de gros morceaux de bois provenant de différentes sources et la distribution du bois parmi les zones d'influence des petits cours d'eau dans un bassin versant de 4^{e} ordre relativement vierge et situé dans le centre des chaînes côtières de l'Oregon. Dans le bras principal du ruisseau Cummins, le bois provenait de sources situées de part et d'autre du cours d'eau immédiatement adjacentes au chenal ou de sources situées plus haut sur les pentes d'où il était entraîné par des glissements de terrain ou le transport de débris sur une distance de plus de 90 m à partir du chenal. Environ 65 % du nombre de morceaux et 46 % du volume estimé de bois provenaient de plus haut sur les pentes. Les sources situées aux abords du cours d'eau contribuaient environ 35 % du nombre de morceaux de bois et 54 % du volume estimé de bois. Le volume moyen estimé des morceaux de bois provenant de plus haut sur les pentes représentait environ le tiers de celui des morceaux de bois provenant des abords du cours d'eau. Les morceaux de bois provenant de plus haut sur les pentes se retrouvaient principalement dans les tronçons mitoyens des cours d'eau et dans les zones d'influence qui avaient le plus de contact avec le chenal correspondant au débit d'étiage. Les morceaux de bois provenant des abords du cours d'eau étaient plus également distribués parmi les tronçons examinés et se retrouvaient surtout dans les zones d'influence qui avaient le moins de contact avec le chenal correspondant au débit d'étiage. Nos résultats indiquent que les études antérieures qui ont examiné seulement les sources de bois situées aux abords du cours d'eau sont peu applicables pour élaborer et évaluer des approches d'aménagement en zone riparienne dans les endroits sujets aux glissements de terrain. Le fait de ne pas tenir compte des sources potentielles de bois provenant de plus haut sur les pentes pourrait expliquer la diminution des gros morceaux de bois dans les cours d'eau du Nord-Ouest du Pacifique.

[Traduit par la Rédaction]

Introduction

Large wood is an important element of stream and river ecosystems. It forms and influences the size and frequency of habitat units (i.e., pools and riffles) (Bilby and Ward 1991). Wood controls the storage and transport of sediment (Keller and Swanson 1979; Bilby and Bisson 1998) and organic matter (Bilby and Ward 1989). It also provides a substrate for macroinvertebrates (Wallace et al. 1995; Bilby and Bisson 1998), and changes in the amount of large wood af-

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fect the abundance, biomass, and movement of fish (Fausch and Northcote 1992; Harvey et al. 1999; Roni and Quinn 2001).

Wood enters streams via chronic and episodic processes (Bisson et al. 1987). Chronic processes, such as tree mortality and bank undercutting (Grette 1985; Murphy and Koski 1989), generally deliver single pieces or relatively small numbers of trees at frequent time intervals. Episodic processes usually add large amounts of wood to streams rapidly in large but infrequent events, such as windthrow (Harmon et al. 1986), wildfire (Agee 1993), severe floods, and landslides and debris flows (Keller and Swanson 1979; Benda et al. 2002, 2003*a*).

Examinations of the sources of wood in streams (e.g., Murphy and Koski 1989; McDade et al. 1990; Robison and Beschta 1990; Van Sickle and Gregory 1990) have focused on chronic input from the immediately adjacent riparian zone. Such studies found that the vast majority of the wood was derived from within a distance equal to the height of streamside trees. These did not consider episodic sources of wood or found that it was only a small part of the total wood input (Murphy and Koski 1989).

In steep forested terrain of the Pacific Northwest, landslides and debris flows are potentially important mechanisms for delivering sediment and wood from hillslopes and small headwater channels to valley-bottom streams (Keller and Swanson 1979). Several studies have examined the effect of mass movement events on stream channels, focusing primarily on the impacts of sediments (Hogan et al. 1998; Benda and Dunne 1997*a*, 1997*b*). May (2002) examined the impact of landslides and debris flows from headwater streams on stream channels in the Oregon Coast Range and found that in some cases, large wood was delivered to fish-bearing streams. However, she did not identify the features of the watersheds in which wood was delivered to fish-bearing streams nor did she quantify the amount of upslope-derived wood or compare it with the amount of wood derived from chronic sources.

Management of riparian zones on small headwater streams is currently the focus of consideration by resource managers and agencies, regulatory agencies, and policy makers in the Pacific Northwest of the United States, Alaska, and British Columbia. Small headwater streams are generally nonfish bearing, can include both perennial and intermittent streams, and may constitute up to 90% of the stream network's length (Gomi et al. 2002). Activities in and management of riparian zones for these streams are generally unregulated.

Our understanding of the ecological role of small headwater streams and the riparian zones along them is relatively limited at present (Gomi et al. 2002). Small streams and the associated riparian zone provide habitat for several species of native amphibians and other fauna (Kelsey and West 1998) and may be important sources of food and energy for juvenile fish (Wipfli and Gregovich 2002). Sediment (May 2001) and organic materials (Bilby and Ward 1991) are stored in these streams, often as a result of wood accumulations. The potential contribution of wood to larger streams from headwater streams has not received much consideration, however.

The purpose of this study was to identify sources of wood found in Cummins Creek, which drains a watershed in coastal Oregon that has limited impacts from land management activities. Specifically, we determined (*i*) the percentage of the volume and number of pieces of wood that were delivered from upslope areas by landslides and debris flows and from streamside-adjacent riparian areas; (*ii*) the mean volume of pieces of wood being delivered from the different sources; and (*iii*) the distribution of wood from the different sources in zones of influence on the channel.

Materials and methods

Study site

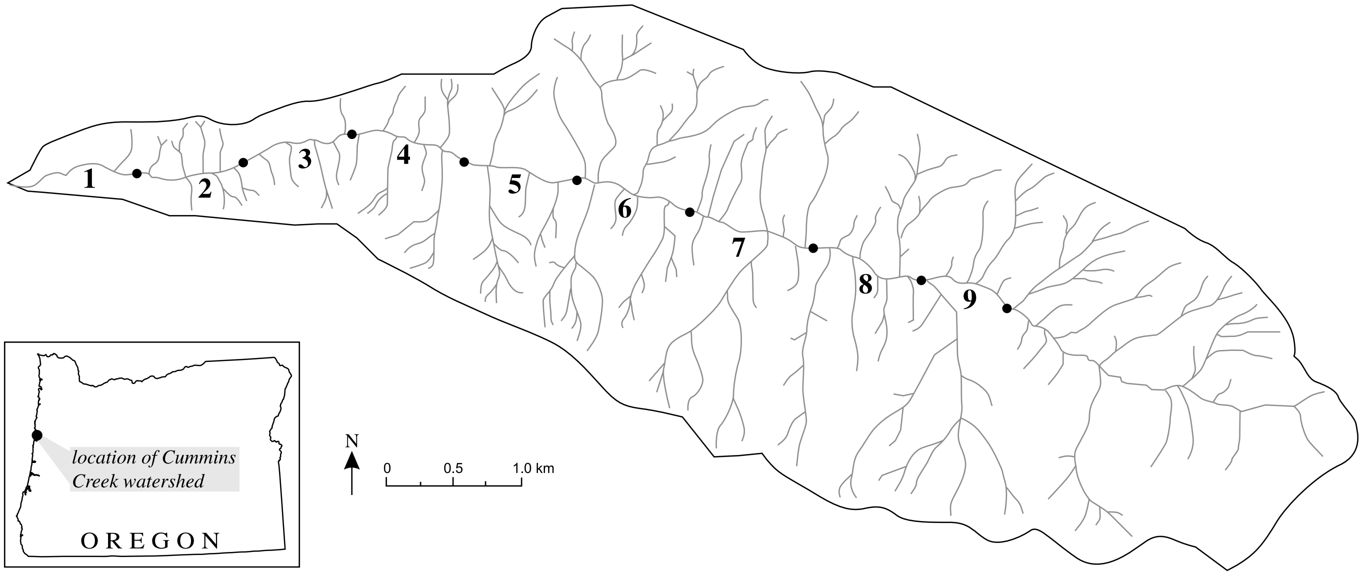
Cummins Creek is a fourth-order stream on the central Oregon coast that empties directly into the Pacific Ocean (Fig. 1). The watershed area is 21.5 km^2. Gradient ranges from 1.2% in the lower portion to 3.6% (mean 2.5%). Summer flows average 0.8 m^3/s. The underlying geology is basalt. Cummins Creek basin was designated as a federal wilderness area and is pristine except for small clear-cut timber harvest units from the late 1950s and early 1970s that total 6% of the watershed area (Fig. 1). Upslope trees are primarily Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). These trees are 150–160 years old, dating from the last large wild fire (Martson 1980). Sitka spruce (*Picea sitchensis* (Bong.) Carrière), red alder (*Alnus rubra* Bong.), and big leaf maple (*Acer macrophyllum* Pursh) dominate the riparian zone and are older than trees outside of the riparian zone. Fish found in Cummins Creek include coho salmon (*Oncorhynchus kisutch*), steelhead (*Oncorhynchus mykiss)*, coastal cutthroat trout (*Oncorhynchus clarki*), and sculpins (*Cottus* spp.).

Data collection and analysis

Data on large wood in Cummins Creek were collected in July 1993. The survey began at the head of tidewater and extended upstream in the main stem to river kilometre 8.7 (Fig. 1), where a large natural landslide deposit limited the upper distribution of anadromous salmonids. Each reach was 1 km in length except for the last one, which was 0.7 km.

Pieces of wood were classified as either streamside derived or upslope derived. Streamside pieces came from the riparian zone immediately adjacent to the surveyed channel. Such pieces were usually intact, had the root wad attached, and were associated with an identifiable root-throw pit from which the piece originated. Upslope pieces of wood originated in areas off the valley floor and were delivered to the surveyed channel by mass movements. Upslope pieces were usually broken and debarked and were often located in aggregates at or near tributary junctions. Each piece of wood was identified as occurring singly or in an aggregate, defined as a collection of two or more pieces. Wood pieces in one large aggregate (approximately 25 000 m^3) were not included in the analysis because these were delivered by a debris flow originating in a clear-cut timber harvest unit from 1967, one of the few from the limited past management activity in the basin. The type of habitat unit (i.e., pool riffle, glide, or side channel (Hawkins et al. 1993)) in which a piece was located was also recorded.

Fig. 1. Location of Cummins Creek. Numbers are sampled reaches.



Each piece of wood that was ≥3 m long and ≥0.3 m in diameter at one-third of the distance from the widest end was counted. Root wads were counted if they were ≥2 m long and ≥0.3 m in diameter at one-third of the distance from the widest end. The length and mean diameter of each piece were estimated visually by a single observer (E.V.M.). Dimensions were also measured with a tape for 3 of every 25 pieces. A calibration factor of the ratio of the estimated value to the measured value was developed from these measures to correct for observer bias (sensu Hankin and Reeves 1988). The bias-corrected estimates for the length and radius were used to estimate the volume of each piece, which was calculated using the formula for a cylinder, with the radius of the piece determined at one-third the distance from the widest end.

Although the number of pieces of wood in each aggregate was counted, dimensions of every piece in larger aggregates could not reasonably be estimated. Consequently, the total volume of wood pieces in each aggregate, regardless of aggregate size, was determined with bootstrapping techniques. For each aggregate, 2000 samples were drawn with replacement from known volume data for wood pieces with estimated dimensions and of the appropriate source type. The size of each sample was equal to the number of pieces in that aggregate. The median value of total volume from the bootstrapped sample distribution was then assigned to the aggregate. The approach was evaluated using only smaller aggregates, i.e., those with estimated dimensions for each piece, by comparing the total volume estimated from bootstrapping with that derived from summing the volumes of component pieces. The total bootstrapped volume for these aggregates exceeded the summed volume estimate by only 0.01%.

Differences between the mean volumes of wood pieces by source type were evaluated using randomization of known piece volumes. The volume of each piece was randomly assigned to either riparian or upslope sources in proportion to observed wood piece counts to generate a test statistic distribution (2000 iterations). The test statistic was the difference in mean volume between wood source types. Significance was assessed as the probability of obtaining a difference in means greater than or equal to the observed difference with reference to the randomized distribution.

The position of the wood in one of four zones of influence (Robison and Beschta 1990) (Fig. 2) was also recorded. Zone 1 was the low-flow channel. Here, large wood influences aquatic habitat throughout the year. Large wood in Zone 2 was within the bank-full width but outside Zone 1. Wood in this zone influences stream hydraulics and habitat during high water. Pieces in Zone 3 were suspended over the bank-full channel. Wood in this zone is likely to move into Zones 1 and 2 in the future. Wood in Zone 4 was on the adjacent floodplain, outside the bank-full width. Wood in this zone may eventually move into Zones 1 and 2. It also anchors pieces found in other zones.

Results

There were an estimated 1384 pieces of large wood in the lower 8.7 km of main stem Cummins Creek examined in this study. Of these, 905 (65.4%) were from upslope sources and 479 (34.6%) were from streamside sources (Table 1). Streamside-derived pieces were 53.6% and upslope-derived pieces were 46.4% of the estimated total volume. The estimated mean volume of streamside pieces was almost three times that of upslope-derived pieces (Table 2). The null hypothesis of equal mean volumes was rejected (P = 0.0); the observed value for the difference in mean volume per piece was 8 m^3, but the median and maximum of the distribution for randomized differences in mean volumes per piece were 0 and 3 m^3, respectively. Approximately one-quarter of the wood (26.9% of pieces and 25.2% volume) in Cummins Creek occurred as aggregates, and most of this was from upslope sources (Table 3).

The longitudinal distributions of volume of each source type were significantly different (χ^2, df = 8, P < 0.01) (Fig. 3). The largest percentage (50.9%) of the estimated volume of upslope-derived wood was found in reaches 5 and

Fig. 2. Zones of influence of wood. (Source: Robison and Beschta (1990), Fig. 2. Reproduced with the permission of the Minister of Public Works and Government Services Canada, 2003.)

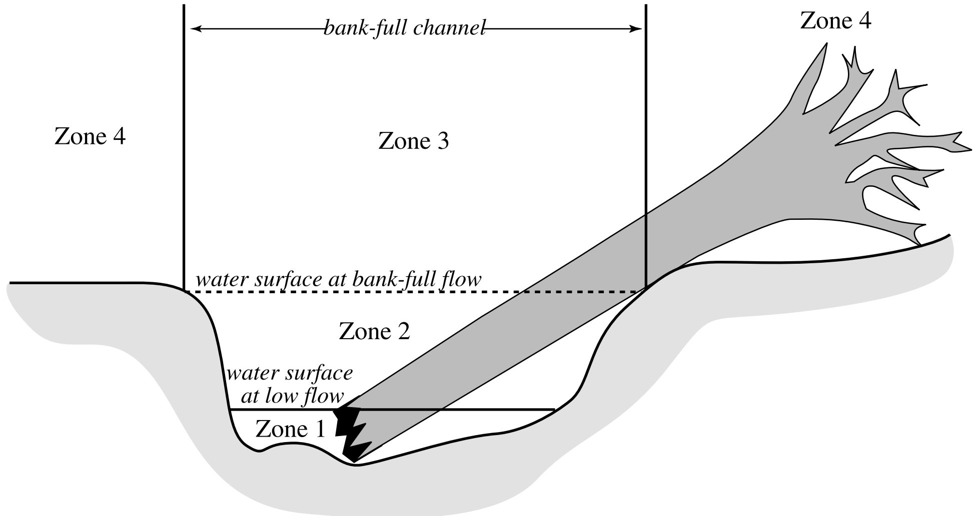


Table 1. Estimated total number and volume of pieces of wood from streamside and upslope sources in Cummins Creek, Oregon.

Wood source	Total no. of pieces	Total vol. (m^3)
Streamside	479	7 090
Upslope	905	6 147
Total	1 384	13 237

Table 2. Estimated mean volume of individual pieces of wood from streamside and upslope sources in Cummins Creek, Oregon.

Wood source	No. of pieces	Mean (SD) vol./piece (m^3)
Streamside	449	15.2 (20.2)
Upslope	563	5.4 (4.3)
Total	1012	9.8 (14.7)

6 (Fig. 1), which were in the middle of the area surveyed. Streamside-derived wood generally declined moving upstream, but it was more evenly distributed along the length of the stream than were upslope-derived pieces (Fig. 3). The greatest proportion of the estimated total volume of streamside-derived pieces was in the lower four reaches (i.e., reaches 1–4). These reaches contained 63.9% of the total volume of streamside-derived wood.

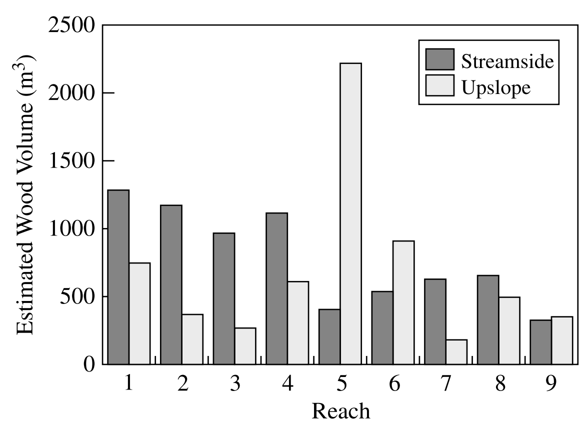
The proportion of wood volume from the different sources found in the various habitat unit types varied. Streamside-derived pieces accounted for 68–72% of the total volume of wood in pools, glides, and side channels (Table 4). In riffles, slightly more wood came from upslope sources (53%) than from streamside sources (47%) (Table 4).

The distribution of the estimated volumes of wood in the influence zones differed among the source types (χ^2, df = 3, $P < 0.01$). Upslope-derived wood volume was predominately in Zones 1 and 2 (Fig. 4), which have the most contact with

Table 3. Estimated volume of wood occurring in aggregates from streamside and upslope sources in Cummins Creek, Oregon.

Wood source	No. of pieces in aggregates	Total aggregate vol. (m^3)
Streamside	30	252
Upslope	342	3087
Total	372	3339

Fig. 3. Estimated volume (m^3) of wood from streamside and upslope sources in Cummins Creek, Oregon. See text for definitions of wood sources.



the low-flow channel. The greatest proportion of the volume of streamside-derived wood was in Zone 4 (Fig. 4), which has no contact with the low-flow channel. The smallest proportion was in Zone 1.

Discussion

Upslope-derived wood constituted a substantial proportion of the volume and number of pieces of large wood in

Table 4. Percentage of volume of wood from different sources found in types of habitat units in Cummins Creek, Oregon.

Wood source	Pools	Riffles	Glides
Streamside	68	47	68
Upslope	32	53	32

Cummins Creek. This finding is similar to results of recent studies in Washington and northern California. Landslides delivered more than 80% of the number of large wood pieces to a stream in the Olympic National Park, Washington (Benda et al. 2003*b*), and in the Redwood National Park, California (Benda et al. 2002).

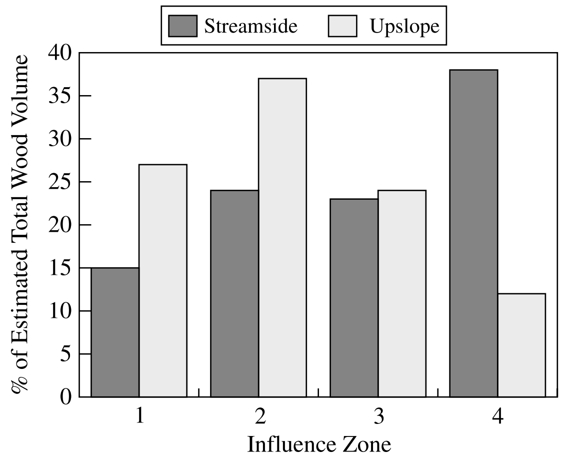
The difference between the mean volume of the pieces of wood of each source type is likely attributable to the fire history of Cummins Creek. Hillslopes are more susceptible to fire and burn more frequently than streamside riparian zones (Agee 1993). Thus, trees in the streamside riparian zone may be disturbed less frequently and achieve larger sizes than upslope trees. The last major wildfire in Cummins Creek occurred 150–160 years ago (Martson 1980) but did not burn the streamside riparian zone.

Topographic features of a watershed influence the relative contribution of upslope sources of wood. Steeper, more highly dissected watersheds will likely have a greater proportion of wood coming from upslope sources than will watersheds that are less dissected or steep. Murphy and Koski (1989) and Martin and Benda (2001) found that upslope sources were not an important contributor to the total amount of wood in a southeast Alaskan stream. The watershed examined by Martin and Benda (2001) had a wide valley floor, and wood from upslope was deposited along valley walls, away from the main channel. Even in watersheds with a greater propensity to deliver wood via landslides, the ability of upslope channels to deliver wood to fish-bearing streams will vary. Benda and Cundy (1990) identified the features of first- and second-order streams with the greatest potential to deliver materials to fish-bearing streams in the central Oregon coast. The primary features are channel gradients of >8–10% and tributary junction angles of <45°.

The difference in the longitudinal distribution of the two sources of wood can be explained, at least in part, by topographic features in Cummins Creek. Streamside-derived wood was most prevalent in the lower reaches of the watershed. There, the valley floor is wider than any other part of the watershed, and the channel has a greater potential to move across the valley floor. Additionally, the surrounding hillslopes are less steep than in the upper portions of the watershed and tributaries are smaller. The combination of these features decreases the potential contribution of upslope wood in this area compared with upstream areas. The middle portion of the network had the greatest amount of upslope-derived wood. There, the valley floor was not as wide as the lower portion, but there were larger, steeper tributaries. These features favored the dominance of wood from upslope sources.

Topographic features of Cummins Creek also influenced the distribution of the wood sources among the zones of influence. Wood from upslope sources was found predominately in Zones 1 and 2, which are closest to the stream. Reaches where upslope wood accumulated had relatively narrow valley floors, so landslides deposited wood closer to the active channel. The largest proportion of the volume of streamside-derived wood was in Zone 4. This resulted because of the relatively large trees and the wide valley floor in reaches where many of the streamside-derived trees were found. Thus, when streamside-derived trees fell, they often spanned across all influence zones, because a relatively large proportion of a tree remained on the valley floor. This latter result differs from findings of Robison and Beschta (1990) in a similar-sized stream in southeast Alaska. They found only 39% of the total wood volume in Zones 3 and 4 and attributed this to the fact that the bank-full width exceeded the size of the average piece length by 1.8–3.1 times (Robison and Beschta 1990). In contrast, the average length of streamside-derived wood exceeded the bank-full width in Cummins Creek.

Fig. 4. Percentage of estimated total wood volume of upslope and streamside-derived wood in the influence zones in Cummins Creek, Oregon. See text for definitions of wood sources and influence zones.



Although only one-quarter of the total wood in Cummins Creek was in aggregates, this wood may play a disproportionately important ecological role. Aggregates can impound gravel and water, which creates sites of complex in-channel habitat (Hogan et al. 1998; Abbe and Montgomery 1996). Aggregates may be more successful at forming large pools than all but the largest individual pieces of wood (Hauer et al. 1999). Larger pools formed by aggregates may be important habitat for juvenile salmonids during low-flow periods (Sedell et al. 1984) and during winter (Rodgers 1986). Gravel accumulations behind aggregates may also provide sites for vegetation colonization and forest establishment (Naiman et al. 1998) and provide habitat for several wildlife species (Kelsey and West 1998). Wood from upslope sources constitutes the majority of aggregates in Cummins Creek.

Riparian sources provided most of the wood volume in pools, but upslope sources provided a substantial percentage (approximately one-third or more) of the wood volume in each habitat type. This appears to contradict findings of Montgomery et al. (2003) that only 3% of all logjams (i.e., equivalent to aggregates in our study) in old-growth forest streams were created by debris flows and that 4% of the pools in Cummins Creek were formed by debris-flow derived logjams. Differences between the methods of the two studies may account for these perceived inconsistencies in results. The first methodological difference is that Montgomery et al. (2003) classified "…each jam based on the process observed or interpreted to have triggered the jam formation." (p. 78), but we identified the origin of each wood piece, regardless of whether it was considered responsible for forming a jam. The second such difference was that Montgomery et al. (2003) established the percentage of pools formed by different sources, whereas we determined the source of all wood volume in each habitat type. Debris flows may not be the primary source of wood that forms logjams or pools in old-growth systems; however, the substantial volume of upslope-derived wood in Cummins Creek suggests that upslope sources contribute appreciably to habitat complexity.

We believe that it is important to cautiously interpret the results of many previous studies on the distance from streams that wood originates, particularly in areas where landslides and debris flows are major processes. Consistent with stated objectives, previous studies of wood sources either did not address wood from upslope sources (e.g., Van Sickle and Gregory 1990) or avoided study reaches that were impacted by landslides (McDade et al. 1990; F. Swanson, personal communication). However, these and other studies (e.g., Robison and Beschta 1990) are often misinterpreted to mean that all wood is from streamside sources. The finding that a substantial proportion of the wood in Cummins Creek came from upslope sources suggests that studies examining only streamside sources of wood (e.g., McDade et al. 1990; Robison and Beschta 1990) have limited applicability for developing and evaluating riparian management policies for landslide-prone areas.

Several recent studies found that streams flowing through second-growth forests have reduced amounts of large wood compared with pretimber harvest levels (e.g., Andrus et al. 1988; Ralph et al. 1994; McHenry et al. 1998). A primary reason given for this decline is reduced recruitment of wood from streamside riparian zones and (or) recruitment of smaller pieces of wood, which are more mobile or decay faster than larger pieces. Another possible factor for this decline suggested by the present study is the loss or reduction of input from upslope sources. Past, and many current, management policies and regulations regarding riparian zones addressed only the riparian zone along fish-bearing and larger channels (Murphy 1995). Where regulations failed to address headwater streams, vegetation was removed from along them. The reduction or elimination of upslope sources of wood likely contributed to the overall decline in the amount of wood in larger streams. Reduction of large wood in streams in the Pacific Northwest of the United States has several ecological consequences by altering the physical (Smith et al. 1983; Montgomery et al. 1995, 1996) and biological (Reeves et al. 1993) components of aquatic ecosystems.

Recent reviews of riparian management policies and regulations in the Pacific Northwest of the United States have called for including headwater streams in riparian management policies and plans (Murphy 1995; Independent Multidisciplanary Science Team 1999). However, most current management approaches for aquatic ecosystems rely on only streamside sources for the recruitment of wood. Leaving trees along headwater channels would be expected to increase the potential delivery of wood to higher order, fish-bearing streams. Future management and restoration efforts that focus on processes, such as the delivery of wood from all sources, including upslope, rather than meeting individual in-channel habitat targets, such as a specified number of large wood pieces, may ultimately be more effective in creating self-sustaining ecosystems that provide favorable conditions for aquatic and riparian-dependent organisms (Reeves et al. 1995; Ebersole et al. 1997; Beechie and Bolton 1999).

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