Large wood recruitment and redistribution in headwater streams in the southern Oregon Coast Range, U.S.A.[1]

Christine L. May and Robert E. Gresswell

Abstract: Large wood recruitment and redistribution mechanisms were investigated in a 3.9 km^2 basin with an old-growth *Pseudotsuga menziesii* (Mirb.) Franco and *Tsuga heterophylla* (Raf.) Sarg. forest, located in the southern Coast Range of Oregon. Stream size and topographic setting strongly influenced processes that delivered wood to the channel network. In small colluvial channels draining steep hillslopes, processes associated with slope instability dominated large wood recruitment. In the larger alluvial channel, windthrow was the dominant recruitment process from the local riparian area. Consequently, colluvial channels received wood from further upslope than the alluvial channel. Input and redistribution processes influenced piece location relative to the direction of flow and thus, affected the functional role of wood. Wood recruited directly from local hillslopes and riparian areas was typically positioned adjacent to the channel or spanned its full width, and trapped sediment and wood in transport. In contrast, wood that had been fluvially redistributed was commonly located in mid-channel positions and was associated with scouring of the streambed and banks. Debris flows were a unique mechanism for creating large accumulations of wood in small streams that lacked the capacity for abundant fluvial transport of wood, and for transporting wood that was longer than the bank-full width of the channel.

Résumé : Le recrutement et les mécanismes de redistribution des gros débris ligneux ont été étudiés dans un bassin de 3,9 km^2 supportant une forêt ancienne de *Pseudotsuga menziesii* (Mirb.) Franco et de *Tsuga heterophylla* (Raf.) Sarg. située dans la partie sud de la chaîne côtière de l'Oregon. La dimension du cours d'eau et la configuration topographique ont une influence déterminante sur les processus de distribution des débris ligneux dans le réseau hydrographique. Dans les petits canaux colluviaux qui drainent les versants abrupts, le recrutement de gros débris ligneux est dominé par les processus associés à l'instabilité des pentes. Dans les canaux alluviaux plus larges, le processus dominant de recrutement est le chablis dans la zone riveraine locale. Par conséquent, les canaux colluviaux reçoivent des débris ligneux provenant de plus haut sur les pentes que les canaux alluviaux. Les processus d'apport et de redistribution influencent la position des morceaux de bois par rapport à la direction de l'écoulement et affectent par conséquent la fonction des débris ligneux. Les débris ligneux recrutés directement des pentes et des zones riveraines locales sont typiquement soit dans une position adjacente, soit s'étendent sur la pleine largeur du cours d'eau et retiennent les sédiments et les débris ligneux en mouvement. Par contre, les débris ligneux redistribués par les eaux sont normalement situés au milieu des cours d'eau et associés à l'affouillement du lit et des berges du cours d'eau. Le transport des débris ligneux constitue un mécanisme unique pour créer d'importantes accumulations de bois dans les petits cours d'eau qui n'ont pas la capacité de transporter beaucoup de débris ligneux ou des morceaux de bois plus longs que la pleine largeur des berges du cours d'eau.

[Traduit par la Rédaction]

Introduction

The transfer of wood from forests to streams is a major linkage between terrestrial and aquatic ecosystems (Lienkaemper and Swanson 1987). Previous studies have shown the important role large wood plays in the structure and function of mountain streams (Keller and Swanson 1979; Harmon et al. 1986; Bisson et al. 1987; Ralph et al. 1994; Bilby and Bisson 1998); however, little is known about the relative contribution of wood delivered by pro-

Received 11 June 2002. Accepted 7 January 2003. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 30 June 2003.

C.L. May.[2,3] Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR 97331, U.S.A.
R.E. Gresswell. U.S. Geological Survey, Forest and Rangeland Ecosystem Science Center, 3200 SW Jefferson Way, Corvallis, OR 97331, U.S.A.

[1]This paper was presented at the symposium Small Stream Channels and Riparian Zones: Their Form, Function and Ecological Importance in a Watershed Context held 19-21 February 2002, The University of British Columbia, Vancouver, B.C., and has undergone the Journal's usual peer review process.
[2]Corresponding author (e-mail: clmay@fs.fed.us).
[3]Present address: USDA Forest Service Pacific Southwest Research Station, 1700 Bayview Drive, Arcata, CA 95521, U.S.A.

 doi: 10.1139/X03-023

cesses occurring in the local riparian area compared to upstream and upslope sources of wood. Additionally, there is a scarcity of information on how wood recruitment processes differ in channels of different size and landscape position. Previous research on wood recruitment processes (Keller and Swanson 1979; Murphy and Koski 1989) and the source distance of wood to stream channels (Murphy and Koski 1989; McDade et al. 1990) have primarily focused on wood recruited directly from the local riparian area in alluvial streams. In mountainous terrain of the Pacific Northwest, landslides on hillslopes and debris flows in small colluvial channels also have the potential to deliver large quantities of wood to alluvial rivers (Swanson and Lienkaemper 1978; Keller and Swanson 1979; May 2002). Quantification of wood recruitment and redistribution mechanisms, and ways in which they vary spatially in a basin, may be useful for determining how and where to protect the sources of wood to streams (Martin and Benda 2001).

In recent years it has become increasingly apparent that to maintain complex aquatic habitat, guidelines for forest practices require measures to preserve physical and biological linkages between streams, riparian zones, and uplands (Independent Multidisciplinary Science Team 1999). Upland forests and headwater streams can influence water quantity and quality, invertebrate and detritus inputs, and physical habitat characteristics throughout the drainage network. Headwater streams typically do not directly support fish but they can have a strong influence on the rate of sediment and wood delivered to larger rivers that provide habitat for numerous aquatic organisms.

The majority of the channel network in mountainous terrain is composed of first- and second-order channels (Shreve 1969) that typically have ephemeral or intermittent streamflow and store large volumes of wood and colluvial sediment. Several studies have documented a systematic increase in large wood abundance with decreasing stream size, along with a corresponding decrease in the mean size of pieces as stream size decreases (Keller and Swanson 1979; Bilby and Ward 1989; McDade et al. 1990). The frequency and residence time of log jams also tends to increase as drainage area decreases (Martin and Benda 2001).

Past studies in the Oregon Cascade Range (Swanson et al. 1982) and in central Idaho (Megahan and Nowlin 1976) have indicated that chronic fluvial processes in first- and second-order streams transport a relatively small quantity of sediment and wood. Instead, low-order streams can undergo long periods of storage of sediment and wood that can be episodically transported by debris flows (Swanson and Lienkaemper 1978; May and Gresswell 2003). Because debris flows are a stochastic process, the relative contribution of debris flow transported wood will have a great deal of spatial and temporal variability. In 11 third- through fifth-order streams in the Oregon Coast Range, the contribution of wood from debris flows ranged from 11 to 57% of the total volume of wood in the channel for basins that had a broad range of forest age-classes and land-use history (May 2002). Because debris flows are primarily a mechanism for redistributing in-stream wood (May 2002) and because wood can influence the runout of debris flows (Lancaster et al. 2001), it is important to understand the sources of wood in this portion of the network.

The goal of this study was to gain insight into the relative contribution of processes that recruit and redistribute wood and to understand how these processes vary spatially in a basin. Specific research questions included the following: (*i*) Do processes that deliver and redistribute wood differ in small colluvial channels compared with larger alluvial channels? (*ii*) Do proximal and distal controls on wood delivery differ for colluvial and alluvial channels? (*iii*) How do input and redistribution processes influence the functional role of wood in the channel?

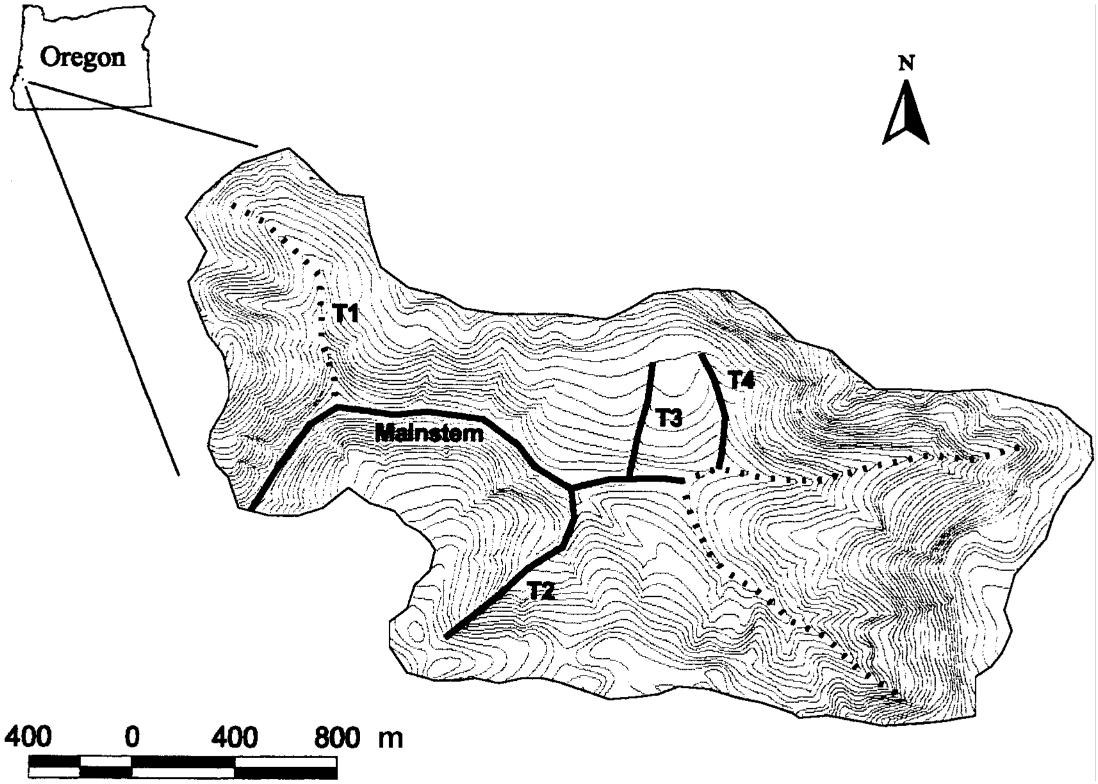
This study focused on a contrast between small colluvial channels and larger alluvial channels because they occupy vastly different process domains. Process domains are spatially identifiable areas characterized by distinct suites of geomorphic processes, and systematic differences in the type and frequency of disturbance and habitat-forming events (Montgomery 1999). Colluvial channels are high gradient and directly drain the steep hillslopes. These channels are tightly constrained by the adjacent hillslopes and have small drainage areas (<1 km^2). Colluvial channels typically have ephemeral or intermittent streamflow, poorly sorted, angular to subangular substrates, and an absence of alluvial bedforms. Alluvial channels have a low to moderate gradient, and commonly have perennial streamflow and alluvial bedforms. Alluvial channels in the Oregon Coast Range are typically third-order or larger channels, with drainage areas >1 km^2 (Montgomery and Foufoula-Georgiou 1993).

Study site

The study was conducted in the North Fork of Cherry Creek Research Natural Area (Franklin 1972), a 3.9-km^2 basin in the southern Oregon Coast Range (Fig. 1). Old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don) are present in the portion of the study basin investigated. The mean age of Douglas-fir trees is in excess of 300 years, and the mean diameter at breast height (DBH) ranges from 125 to 175 cm (Franklin 1972). Although tree size varies with site conditions and tree age, a typical old-growth Douglas-fir tree is 50 to 70 m in height (Franklin et al. 1981). The largest identified Douglas-fir tree in Oregon (294 cm DBH, 87 m height) was located on the low elevation valley floor of the mainstem, and tree ring analysis indicated the tree originated in the 1300s. Human influences upon the area are related to road construction and clearcut logging operations in the upper elevations of the basin (Franklin 1972).

The Oregon Coast Range has a maritime climate characterized by wet and relatively warm winters and dry summers. Annual precipitation averages 210 cm, coming mostly as fall and winter rain. The basin is underlain by Tertiary marine sedimentary rocks of the Tyee Formation and is bordered on the west by the Umpqua Formation (Baldwin 1964). The dominant substrate throughout the channel network is gravel and sand-sized particles. Soils in the basin are characterized by deep to moderately deep, steep, gravelly, and loamy soils that formed in colluvium and residuum derived from sedimentary rock (Soil Conservation Service 1989). The basin ranges in elevation from 207 to 451 m.

Fig. 1. North Fork of Cherry Creek basin. Dark solid lines represent the study streams, broken lines represent channels with a history of timber harvest and not investigated. Numerous first-order channels are poorly represented on low-resolution topographic maps and are not highlighted. Contour interval = 10 m.



Materials and methods

All colluvial channels investigated were second-order (Strahler 1964) ephemeral streams that drained steep hillslopes and were tributaries that directly connected to the mainstem, alluvial channel. For this study, first-order streams were delineated on topographic maps where distinct valleys were evident, and the extent of the network was verified in the field by the presence of a definable channel and evidence of fluvial scour. Therefore, first-order streams extended higher up in the drainage network than in studies that based stream order on stream lines from U.S. Geological Survey topographic maps. Our field-based determination of stream order typically resulted in an increase of one or two stream orders compared with map-based determinations.

Three, second-order colluvial tributaries and the entire third-order mainstem of the North Fork of Cherry Creek were investigated (Fig. 1). Tributary 1 was not surveyed because all wood in the channel had been removed by a debris flow that initiated several decades ago in a timber harvest unit at the channel head. Two tributaries in the upper basin were not surveyed because they had been harvested for timber in previous decades.

In the study streams, all downed wood that exceeded 20 cm in mean diameter and 2 m in length, and was in contact with the bank-full channel, was measured. Wood volume was calculated as a cylinder, using the mean piece diameter and total length. Volume calculations were not based on a frustum because the majority of pieces were broken and did not exhibit the taper that would be expected from an intact bole.

Large wood was categorized by the mechanism that delivered it to its current position in the channel network. Categories included (*i*) direct delivery from local hillslopes and riparian areas, (*ii*) fluvial redistribution, (*iii*) debris flow transported, or (*iv*) an unidentified source. Specific recruitment processes for wood derived from local hillslopes and riparian areas were identified by following the in-stream wood up the bole to the rooting location of the tree (Table 1).

Fluvially redistributed wood was identified by the absence of a local growing point of the tree and by the physical trapping of the piece by obstructions in or along the channel, which apparently resulted from transport to the site from upstream. Wood transported by debris flows in the tributaries was identified by deposit morphology, which included large, valley spanning debris dams and debris flow fans. Debris flow deposits were also close to a tributary that had recently been scoured to bedrock. The contribution of wood from debris flows may have been overestimated if fluvially transported wood had accumulated above the deposit. Furthermore, the original source and recruitment process of wood could not be identified if it had been redistributed in the channel.

Identification of wood recruitment and redistribution mechanisms were categorized during a retrospective investigation and were therefore subject to several forms of ambiguity. The wood recruitment category with the greatest

Table 1. Criteria used to identify large wood recruited from processes in the local hillslopes and riparian areas.

Recruitment process	Criteria for classifying
Slope instability	Deposits associated with landslides in hollows and planar sideslopes, streamside landslides, and inner gorge areas with evidence of accelerated soil creep and surface erosionat the rooting site
Natural mortality	Broken boles of standing dead trees
Independent windthrow	Single, uprooted tree
Dependent windthrow	Numerous uprooted trees in a larger windthrow patch, often located further upslope and knocking down trees growing closer to the channel
Bank erosion	Undercut trees rooted in the channel bank
Unknown process	Bole extended into the local forest; however, no recruitment process could be identified

Table 2. Channel characteristics and large wood abundance in colluvial tributaries and the mainstem alluvial channel.

	Mainstem	Tributary 2	Tributary 3	Tributary 4
Stream order (topographically determined)	3	2	2	2
Stream order (USGS stream lines)	2	0	0	0
Stream length sampled (m)	2140	490	400	190
Mean channel width (m)	4.8	3.3	3.6	3.6
Mean valley floor width (m)	16	6	5	6
Mean channel slope (%)	3	19	25	9
Large wood (no./100 m)	34	48	42	37

degree of uncertainty was windthrow. It was assumed that live trees were uprooted by windthrow, and that natural mortality resulted in fragmentation of a standing dead tree. Windthrow may also cause trees to fall that have been weakened by competition or other mortality agents (e.g., insects and disease) that predispose the trees to toppling or breaking (Harmon et al. 1986; Franklin et al. 1987). Furthermore, trees rooted in the channel bank could have been delivered by the combined effects of bank erosion and windthrow (Lienkaemper and Swanson 1987), but all wood from trees rooted in the bank was categorized as bank erosion.

Source distance of wood delivered from the local hillslopes and riparian areas was measured as the total slope distance from the edge of the bank-full channel at a right angle upslope to the growing point of the tree (McDade et al. 1990). Pieces from broken trees that were in direct alignment were followed to the rooting location. If there was uncertainty in the sequences of pieces, no source distance was recorded. Our estimate of the source distance of wood may be an underestimate because trees recruited from closer to the stream may have a higher likelihood of being identified as sources for downed wood than trees growing farther away from the channel.

The identified rooting location was used to quantify the source distance. If a single tree delivered multiple pieces of wood to the channel, all pieces were assigned the same source distance. The distance an individual tree slid downslope from the rooting location was not recorded. Because the exact rooting location could not be identified on landslides, the source distance for wood in landslide deposits was taken from the active channel edge to the headscarp of the landslide. This measurement may overestimate the actual source distance of individual trees previously growing on the landslide.

The location of wood, relative to the flow direction, was recorded for all pieces in contact with the active channel. Categories of piece location included pieces adjacent to the channel bank, mid-channel pieces, pieces that spanned the full width of the channel, or pieces suspended over the channel. The dominant geomorphic function of wood was classified by its interaction with streamflow and sediment. Pieces were classified as being associated with (*i*) streambed scour, (*ii*) stream bank scour, (*iii*) stream bank armor, (*iv*) sediment storage, (*v*) wood storage, (*vi*) side channel formation, or (*vii*) no discernable geomorphic function. Wood storage included the physical trapping of branches and twig accumulations (i.e., small wood) and other pieces of large wood. A single category that represented the dominant function was assigned to each piece.

Results

A total of 1205 pieces of large wood were measured in the channel network (Table 2). Distributions of piece diameter and length were similar in tributaries and the mainstem ($p > 0.1$, Kolmogorov–Smirnov, two-sided, two-sample test). Wood derived from local hillslopes and riparian areas accounted for the majority of pieces (63%) in small colluvial channels (Table 3). The larger alluvial channel received wood from a greater variety of sources, including recruitment from local hillslopes and riparian areas (36%), fluvial redistribution (9%), and debris flow transported wood (33%). In colluvial tributaries, 36% of the pieces had an unidentified source; however, these pieces were typically small and only accounted for 10% of the total volume of wood. In the alluvial channel 22% of pieces had an unidentified source, but they were also small and accounted for only 6% of the total volume of wood. The majority of pieces with an

Table 3. Sources of large wood in the North Fork of Cherry Creek basin.

	Wood pieces (%)		Wood volume (%)		
	Colluvial tributaries	Alluvial mainstem	Colluvial tributaries	Alluvial mainstem	Median piece volume (m^3)
Local hillslopes and riparian areas	63	36	89	74	2.75
Fluvial redistribution	1	9	1	2	0.25
Debris flow transported	—	33	—	18	0.77
Unknown source	36	22	10	6	0.63

Fig. 2. Wood delivered to colluvial (second-order) and alluvial (third-order) channels from different recruitment processes in the local hillslopes and riparian areas.

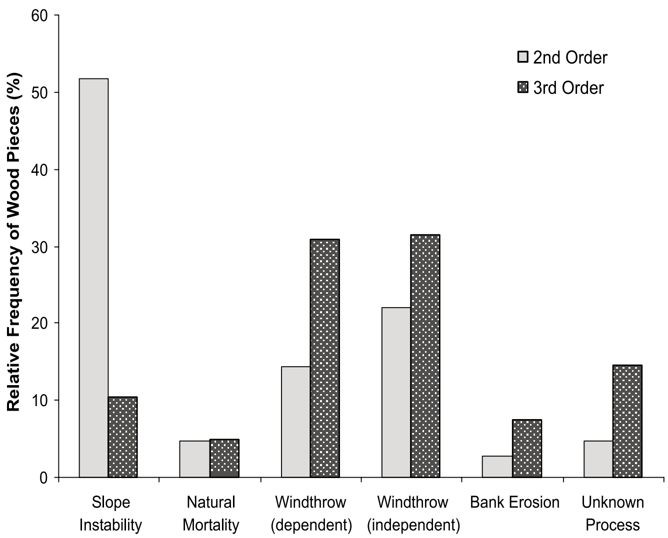
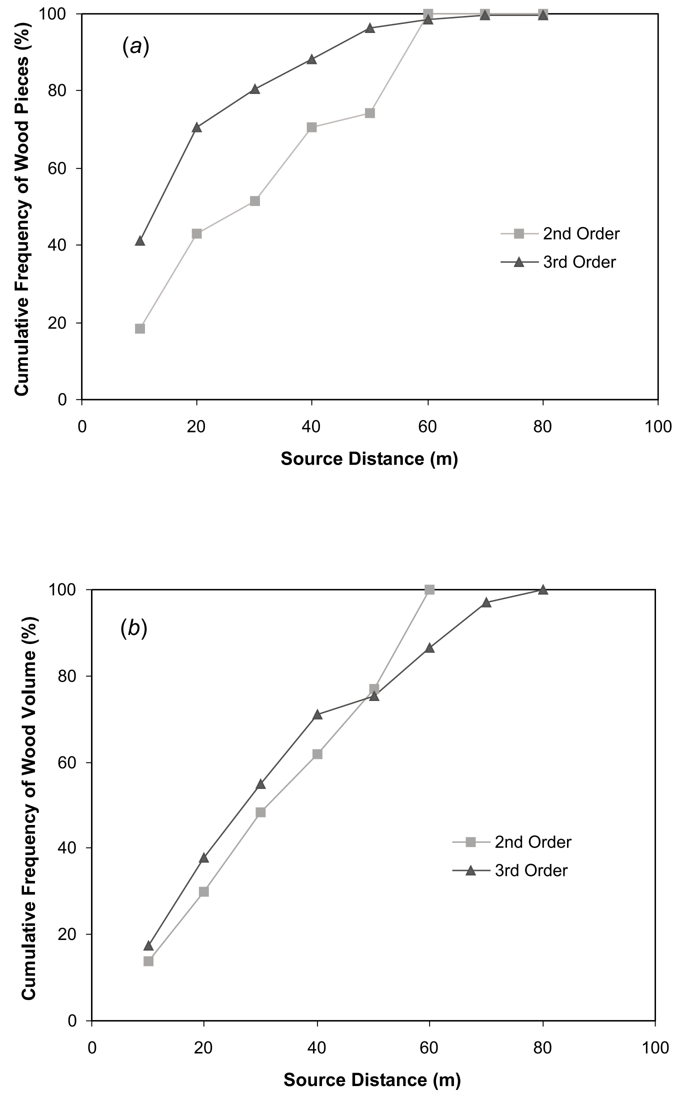


Fig. 3. The source distance of large wood (*a*) pieces and (*b*) volume for second-order colluvial tributaries and the third-order mainstem channel in the North Fork of Cherry Creek basin.



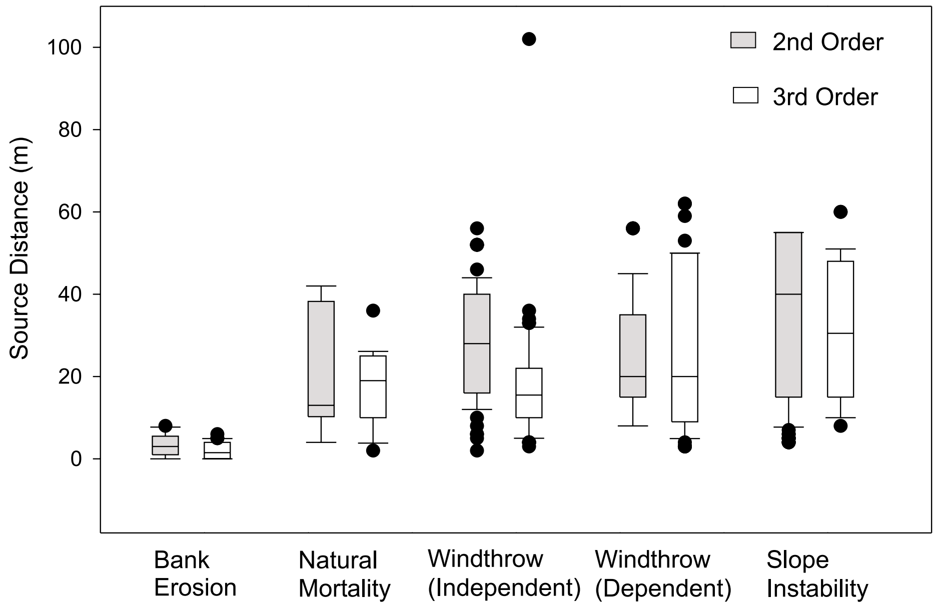
unidentified source appeared to be broken branches or the tops of trees that experienced substantial breakage. Wood that was redistributed by fluvial processes had the smallest median volume per piece (Table 3). Pieces with an unknown source and those transported by a debris flow were intermediate in size, and pieces recruited directly from the local hillslopes and riparian area had the largest median volume. The median volume of wood pieces was significantly different among these sources ($p < 0.05$, Kruskal–Wallis multiple comparisons test). Because larger pieces of wood were recruited from the local hillslopes and riparian areas, these sources of wood had a disproportionately large contribution to the volume of wood in the channel. For example, wood recruited from the local hillslopes and riparian areas accounted for 36% of wood pieces in the alluvial stream, which accounted for 74% of the total volume of wood.

Large wood recruitment from the local hillslopes and riparian areas

Slope instability and windthrow were the dominant mechanisms for wood recruitment to small colluvial channels (Fig. 2). Windthrow was also the dominant recruitment process for wood derived from the local hillslopes and riparian areas along the larger alluvial stream. Field evidence of a broad range in the state of decay for wood recruited by windthrow suggests that input did not occur in a single catastrophic event, but was spread over multiple decades.

Distributions of the source distance of wood pieces were significantly different between colluvial and alluvial channels ($p < 0.05$, Kolmogorov–Smirnov, one-sided, two-sample test) (Fig. 3*a*). The source distance of wood was also significantly different when comparing wood volume between col-

Fig. 4. Box-and-whisker plots of the source distance of large wood with different recruitment mechanisms. Lower boundary of box represents the 25th percentile, mid-line represents the median, and upper boundary of box represents the 75th percentile. Lower whisker represents the 10th percentile, upper whisker represents the 90th percentile, and circles represent outlying points. For windthrow, median source distance was significantly different in second- and third-order channels ($p < 0.05$, Kruskal–Wallis multiple comparisons test). For bank erosion and slope instability, median source distance was significantly different from all other recruitment processes ($p < 0.05$, Kruskal–Wallis multiple comparisons test).



luvial and alluvial channels owing to the extended tail of the distribution ($p < 0.05$, Kolmogorov–Smirnov, one-sided, two-sample test) (Fig. 3*b*). In colluvial streams, 80% of wood pieces and 80% of the total volume of wood originated from trees rooted within 50 m of the channel. In the alluvial channel, 80% of the pieces of wood originated from within 30 m of the channel; however, this accounted for only 50% of the total volume of wood. Source distance was poorly correlated with piece length ($r_s = 0.20$, Spearman's rank correlation), diameter ($r_s = 0.23$), and piece volume ($r_s = 0.26$).

Processes associated with slope instability tended to deliver wood from further upslope than other processes (Fig. 4). In both colluvial and alluvial channels, sources of wood delivered by slope instability extended furthest from the channel (pooled median source distance = 40 m), followed by independent and dependent windthrow (pooled median source distance = 20 m), and natural mortality (pooled median source distance = 18 m), and for obvious reasons bank erosion occurred closest to the channel bank (pooled median source distance = 2 m). Slope instability and bank erosion had significantly different median source distances compared to all other recruitment processes ($p < 0.05$, Kruskal–Wallis multiple comparisons test). Source distances of wood recruited by natural mortality and independent and dependent windthrow were similar ($p > 0.05$, Kruskal–Wallis multiple comparisons test). There were no significant differences in the source distance of wood recruitment processes among stream orders, excluding windthrow ($p > 0.05$, Kruskal–Wallis multiple comparisons test). The median source distance of wood recruited by independent windthrow was significantly longer in colluvial channels than in the alluvial channel ($p < 0.05$, Kruskal–Wallis multiple comparisons test).

Large wood redistribution

Fluvial redistribution of wood was infrequent in the channels we investigated (Table 3). In the mainstem alluvial channel, 38% of all pieces were shorter than the mean bank-full channel width, and 68% of pieces that were fluvially redistributed were shorter than the mean bank-full channel width. In the colluvial tributaries, 16% of pieces were shorter than the mean bank-full channel width; however, only 1% of pieces were moved by fluvial transport. In contrast, 55% of debris flow transported wood was longer than the mean bank-full width of the tributaries.

In the alluvial channel, wood that had been redistributed by fluvial processes or by debris flows had a patchy spatial distribution (Fig. 5). A debris flow in Tributary 1 (Fig. 1) initiated in a timber harvest unit in the 1960s. This debris flow deposit formed a large valley-spanning accumulation in the mainstem, and appeared to trap wood transported from upstream. In contrast, large wood derived from windthrow was more abundant and more evenly distributed spatially throughout the stream.

Large wood function

The primary function of wood in small colluvial channels was sediment storage (40%) and small wood storage (20%); however, 37% of pieces had no interaction with streamflow or sediment (Table 4). A broader range of functions was observed in the alluvial channel, and the majority of pieces were associated with local scour of the streambed (26%) and stream banks (26%). The size of pieces associated with each

Fig. 5. Spatial distribution of large wood along the third-order mainstem of the North Fork of Cherry Creek. Arrow indicates the confluence with Tributary 1.

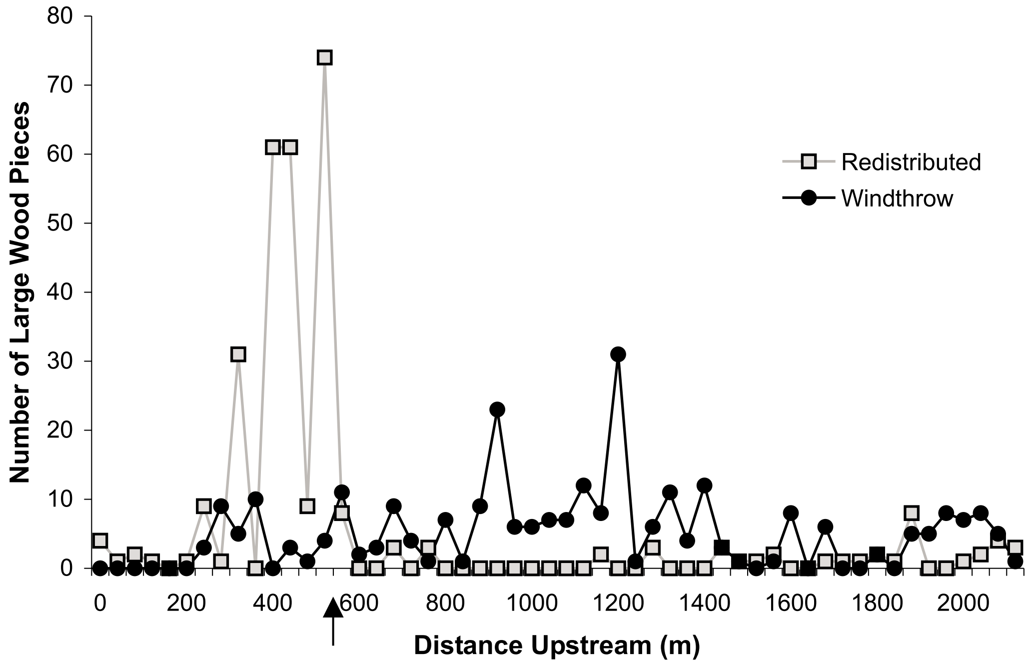


Table 4. Geomorphic function of large wood in the North Fork Cherry Creek basin.

	Colluvial tributaries		Alluvial mainstem	
	Percentage of wood pieces	Mean length of pieces (m)	Percentage of wood pieces	Mean length of pieces (m)
Sediment storage	40	9.8 (9.5)	14	8.8 (9.8)
Wood storage	20	11.2 (10.1)	4	14.5 (12.0)
Streambed scour	0	—	26	8.9 (8.7)
Bank scour	3	14.8 (13.4)	26	10.8 (9.9)
Bank armor	0	—	6	7.2 (7.6)
Side channel	0	—	1	13.4 (5.1)
No discernable function	37	12.7 (9.9)	23	9.5 (9.0)

Note: Numbers in parentheses represent 1 standard deviation.

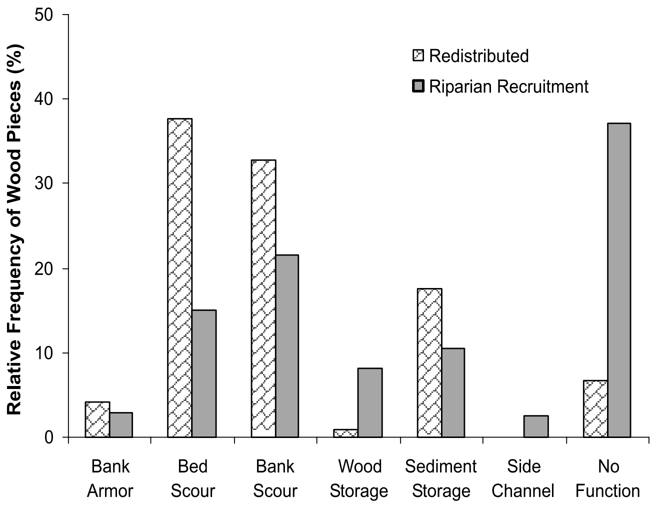
functional category was highly variable, and no consist pattern was observed.

Because of the diversity of recruitment and redistribution processes in the alluvial channel, it was possible to assess the influence of different sources of wood on the position of the wood in the channel. In the alluvial channel, 73% of pieces that had been redistributed were located in mid-channel positions (Table 5). Large wood derived from local hillslopes and riparian areas had a greater variety of positions, but over 56% of pieces were located adjacent to the channel bank. Because the source of wood influenced piece location and size, there was an interaction between wood source and functional category. Redistributed wood was typically smaller in size and was associated with local scour of the stream bed (38%) and stream banks (33%), and almost all (93%) pieces interacted with streamflow and sediment (Fig. 6). Wood recruited directly from local hillslopes and riparian areas had a large proportion of pieces with no discernable interaction with streamflow and sediment (37%), apparently because pieces were located along the edge of the channel. A small number of pieces recruited directly from the local riparian area were important for storing other pieces of large wood that had been redistributed fluvially (8%) and for side channel formation (3%), processes that were not associated with redistributed wood.

Table 5. The position of wood in the mainstem channel for pieces that were recruited directly from local hillslopes and riparian areas compared with pieces that were redistributed by fluvial and debris flow processes.

Position of pieces	Local recruitment (% of pieces)	Redistributed wood (% of pieces)
Adjacent to channel banks	56	24
Mid-channel	11	73
Spanned full width of channel	20	3
Suspended over channel	13	0

Fig. 6. Geomorphic function of large wood in the third-order mainstem for pieces that were recruited from the local riparian area in contrast to pieces that were redistributed by fluvial and debris flow transport.



Discussion

Large wood recruitment from the local hillslopes and riparian areas

Stream size and topographic setting strongly influenced processes that recruited and redistributed wood in the channel network. Processes of slope instability, which included landslides on planar hillslopes and in convergent hollows, streamside landslides, and small inner gorges that had evidence of accelerated toe slope creep were important conveyors of wood from upland forests to small colluvial channels. Windthrow was also an important process for delivering wood to the channel in tributaries and the mainstem. Input of wood from bank erosion was minimal in the study streams, presumably because lateral migration of the channel was limited by the small size of the streams and their small contributing drainage areas. Martin and Benda (2001) reported that wood recruitment from windthrow and chronic mortality was dominant in small drainage basins; however, wood recruitment from bank erosion increased systematically with increasing drainage area.

Causes of tree mortality in upland forest stands influenced the relative contribution of various wood recruitment processes in the channel network. Windthrow has been identified as one of the dominant causes of tree mortality in forests of the Coast Range and Cascade Mountains of Oregon and Washington (Franklin et al. 1987; Franklin and DeBell 1988). This is reflected in the high proportion of wood recruitment by windthrow in both colluvial and alluvial channels. However, other sources of mortality that play a minor role in tree mortality across the landscape were very important sources of in-stream wood. Landslides typically impact a relatively small, discrete patch of the forest but they are efficient conveyors of material downslope to the channel. Similarly, bank erosion is concentrated along the channel and can result in an abundance of wood being recruited to the channel but it may account for only a small portion of tree mortality across the landscape. In larger, laterally migrating rivers, wood recruitment from bank erosion may become the dominant source of wood (Lienkaemper and Swanson 1987; Murphy and Koski 1989). Martin and Benda (2001) estimated that channel processes (i.e., bank erosion) exceeded the maximum mortality of the surrounding forest stands (including windthrow and natural mortality) in drainage areas larger than 20 km^2.

Model predictions by Van Sickle and Gregory (1990) suggest that wood entering a stream from trees growing close to the channel should contribute longer and larger pieces than wood delivered from a greater distance. Our empirical results suggest the opposite. This discrepancy is likely to have occurred because Van Sickle and Gregory (1990) did not consider that smaller trees might be growing closer to the stream. Past studies have found that forest community composition typically varies with distance from the stream (Pabst and Spies 1999; Nierenberg and Hibbs 2000); therefore, the source distance of wood needs to be placed in context with the ways in which tree species and size change with increasing distance from the channel. A low elevation floodplain along the alluvial channel was easily accessible by high flow events, and young alders (<40 years) dominated the near-stream environment. The majority of wood pieces with source distances <10 m in the alluvial channel were young hardwoods. Beyond the floodplain and terrace surfaces, large conifers could be recruited from the upland forest stands, and this relationship may explain the higher volume of wood associated with increased source distances. In contrast, floodplains were absent along colluvial channels, and riparian areas were more representative of upland forest stands, and larger conifers were dominant in the near-stream area.

McDade et al. (1990) is the only other study that empirically determined the source distance of wood to small streams in unlogged watersheds. The source distance of wood for the third-order alluvial channel in our study was similar ($p > 0.1$, Kolmogorov–Smirnov, one-sided, two-sample test) to the results of McDade et al. (1990). However, McDade et al. (1990) found no significant association between source distance and stream order. Results of our study indicated that wood recruitment occurred over longer distances in small colluvial channels (second-order) than in larger alluvial channels (third-order). This is likely to have occurred because McDade's study excluded landslide inputs and therefore much of the wood could have been eliminated from their sample. If landslide-derived wood were excluded from our study we would have excluded 52% of the wood in second-order streams and 10% in third-order streams.

Large wood redistribution

The channels we investigated were small (<5 m wide) relative to the size of in-stream wood. Thus, fluvial redistribution of wood was relatively minor in our study streams, and the spatial distribution was patchy. The spatial distribution of wood in the channel was mainly determined by the pattern of local wood recruitment because the transport capacity of the channel was low. Fluvial transport of wood typically becomes greater in larger rivers because mobile pieces are usually shorter than the bank-full width (Lienkaemper and Swanson 1987). Small streams commonly lack the capacity to transport large wood by chronic fluvial processes; therefore, recruitment from the adjacent hillslopes and riparian areas has a greater influence on the spatial distribution of wood in the channel (Bilby and Ward 1989; Bilby and Bisson 1998). In higher-order streams, the distribution of large wood depends on both local recruitment and upstream sources (McGarry 1994).

Debris flows in colluvial tributaries can be another important source of wood to larger alluvial channels. Colluvial channels lack the capacity to transport wood by fluvial redistribution, and therefore, small streams often store large volumes of wood that can be episodically transported by debris flows. Many first- and second-order colluvial channels in the Oregon Coast Range are susceptible to episodic scouring by debris flows because they drain steep, landslide-prone hillslopes, and the channels are narrow and high gradient. Debris flows deliver sediment, boulders, and wood that can structure the morphology of the receiving channel and are often an important influence on the long-term potential for aquatic habitat development (Everest and Meehan 1981; Reeves et al. 1995; Benda and Dunne 1997; Hogan et al. 1998). Wood delivered by landslides and debris flows may increase in steep V-shaped valleys with high connectivity between hillslopes and channels and between headwater streams and larger rivers, and decrease in broad U-shaped glacial valleys (Martin and Benda 2000).

If past management practices have depleted local sources of wood to larger alluvial rivers, then the relative contribution of wood delivered by debris flows in the colluvial tributaries would be expected to increase. For example, if timber harvest has reduced the recruitment potential of wood from the local riparian area along alluvial rivers, or if wood was purposefully removed from the alluvial river channel, the relative contribution of wood from debris flows would be expected to increase. Wood delivery by landslides and debris flows would also be expected to increase if the removal of forest cover has increased the frequency of mass wasting. This increase in wood delivery would only be expected if legacy wood, such as wood from the previous forest stand that is stored in colluvial channels, was available for transport.

Large wood function

Results of our study indicated that large wood played an important role in storing sediment and small wood in colluvial channels. Similarly, large wood was responsible for the storage of 49% of the sediment in seven small Idaho watersheds (Megahan 1982) and 87% of the sediment in a small stream reach in New Hampshire (Bilby 1981). Large wood may be the cornerstone for storing sediment in steep headwater streams because it provides a physical obstruction to transport in high-energy environments. In the absence of wood, small headwater streams may become a chronic source of sediment to downstream areas. By increasing the sediment storage capacity of the channel, large wood buffers the sedimentation impacts on downstream reaches when pulses of sediment enter headwater streams (Swanson and Lienkamper 1978). In larger alluvial streams, large wood had a broader array of geomorphic functions and was particularly important in pool formation. In both channel types, a large proportion of wood pieces had no discernable interaction with streamflow and sediment at the time of this study; however, these pieces still functioned to increase roughness, create cover and substrate for aquatic organisms, and were a source of organic matter.

Landslides and debris flows were capable of forming large accumulations of wood at locations in the network where fluvial processes may not be competent to transport large quantities of wood. In channels that are narrow or have a small drainage areas, it may not be possible to transport large wood by flotation during high flows (Swanson and Lienkaemper 1978; Martin and Benda 2001). Therefore, landslide and debris flow deposits can provide a unique structure to the channel by forming extremely large accumulations of wood in small streams.

Management implications

There is a critical need to restore ecological processes in riparian and unpland forests that produce and deliver large wood to streams in the Pacific Northwest (Independent Multidisciplinary Science Team 1999). Upland forests and headwater streams can influence water quantity and quality, invertebrate and detritus inputs, sediment retention, and physical habitat characteristics throughout the drainage network. Because these small streams are so abundant and tightly coupled with the steep hillslopes, they can form an important link between hillslope and fluvial processes and between terrestrial and aquatic ecosystems. A distinct suite of geomorphic processes characterizes these small colluvial channels, and patterns of wood recruitment and redistribution are understandably different than in larger alluvial streams.

Various mechanisms can deliver wood from areas that are both proximal and distal to the channel. Source distances of wood recruited directly from local hillslopes and riparian areas varied by position in the network because of differences in recruitment processes, degree of hillslope constriction, and slope steepness. Colluvial channels that drain steep hillslopes are more susceptible to mass wasting and recruited wood from further upslope than larger alluvial channels. As wood is scoured from these small streams, replenishment of similar size wood may not be possible in intensively harvested basins that lack streamside buffers. If timber harvest reduces future recruitment of wood in the interval between debris flows, subsequent failures could be lacking large wood. Forest management that relies primarily on recruitment of wood from riparian buffers along the larger fish-bearing streams may result in much lower levels of wood recruitment than the historic range of conditions (Independent Multidisciplinary Science Team 1999). A restoration approach focused on restoring and managing watershed processes rather than individual habitat characteristics (Beechie and Bolton 1999; Ebersole et al. 1997; Kauffman et al. 1997) may be more effective in producing complex stream channel structure because it provides for a broader array of processes and linkages between processes.

Acknowledgements

This project was funded by the Cooperative Forest Ecosystem Research program, a consortium of the U.S. Geological Survey Forest and Rangeland Ecosystem Science Center, the U.S. Bureau of Land Management, Oregon State University, and the Oregon Department of Forestry, under U.S. Geological Survey grant 3407 7020E 7011TU. The Coos Bay office of the Bureau of Land Management provided the logistical support that made this project possible. Fred Swanson, Tim Beechie, and one anonymous reviewer provided many insightful comments and a thorough review of this manuscript.

References

Baldwin, E.M. 1964. Geology of Oregon. University of Oregon Press, Eugene, Ore.

Beechie, T., and Bolton, S. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries, **24**(4): 6–14.

Benda, L.E., and Dunne, T. 1997. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. Water Resour. Res. **33**(12): 2849–2863.

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 Bisson, P.A. 1998. Function and distribution of large woody debris. *In* River ecology and management: lessons from the Pacific Coastal Ecoregion. *Edited by* R.J. Niaman and R.E. Bilby. Springer, New York. pp. 324–346.

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

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. *In* Streamside management: forest and fishery interactions. *Edited by* E.O. Salo and T.W. Cundy. University of Washington, Institute of Forest Resources, Seattle, Wash. pp. 143–190.

Ebersole, J.L., Liss, W.L., and Frissell, C.A. 1997. Restoration of stream habitats in the western United States: restoration as reexpression of habitat capacity. Environ. Manage. **21**(1): 1–14.

Everest, F.H., and Meehan, W.R. 1981. Forest management and anadromous fish habitat productivity. *In* Transactions of the 46th North American Wildlife and Natural Resources Conference, 21–25 March 1981, Washington, D.C. Wildlife Management Institute, Washington, D.C. pp. 521–530.

Franklin, J.F. 1972. Cherry Creek Research Natural Area. *In* Federal research natural areas in Oregon and Washington: a guidebook for scientists and educators. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Ore.

Franklin, J.F., and DeBell, D.S. 1988. Thirty-six years of tree population change in an old-growth *Pseudotsuga–Tsuga* forest. Can. J. For. Res. **18**: 633–639.

Franklin, J.F., Cromack, K., Jr., Denison, W., McKee, A., Maser, C., Sedell, J., Swanson, F., and Juday, G. 1981. Ecological characteristics of old-growth Douglas-fir forests. USDA For. Serv. Gen. Tech. Rep. PNW-118.

Franklin, J.F., Shugart, H.H., and Harmon, M.E. 1987. Tree death as an ecological process. BioScience, **37**(8): 550–556.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., and Cummins, K.W. 1986. Ecology of course woody debris in temperate ecosystems. Adv. Ecol. Res. **15**: 133–302.

Hogan, D.L., Bird, S.A., and Hassan, M. 1998. Spatial and temporal evolution of small coastal gravel-bed streams: influence of forest management on channel morphology and fish habitats. *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, Highlands Ranch, Colo. pp. 365–392.

Independent Multidisciplinary Science Team. 1999. Recovery of wild salmonids in western Oregon forests: Oregon Forest Practices Act Rules and the Measures in the Oregon Plan for salmon and watersheds. Oregon State University, Corvallis, Ore. Tech. Rep. 1999-1.

Kauffman, J.B., Beschta, R.L., Otting, N., and Lytjen, D. 1997. An ecological perspective of riparian and stream restoration in the western United States. Fisheries, **22**(5): 12–24.

Keller, E.A., and Swanson, F.J. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surf. Process. Landforms, **4**: 361–380.

Lancaster, S.T., Hayes, S.K., and Grant, G.E. 2001. Modeling sediment and wood storage and dynamics in small mountain watersheds. *In* Geomorphic processes and riverine habitat. *Edited by* J.M. Dorava, D.R. Montgomery, B.B. Palcsak, and F.A. Fitzpatrick. American Geophysical Union, Washington, D.C. pp. 85–102.

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

Martin, D.J., and Benda, L.E. 2001. Patterns of instream wood recruitment and transport at the watershed scale. Trans. Am. Fish. Soc. **130**: 940–958.

May, C.L. 2002. Debris flows through different forest age classes in the central Oregon Coast Range. J. Am. Water Resour. Assoc. **38**(4): 1097–1113.

May, C.L., and Gresswell, R.E. 2003. Processes and rates of sediment and wood accumulation in headwater streams of the Oregon Coast Range, USA. Earth Surf. Process. Landforms, **28**: 409–424.

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.

McGarry, E.V. 1994. A quantitative analysis and description of the delivery and distribution of large woody debris in Cummins Creek, Oregon. Research Report, Geosciences Department, Oregon State University, Corvallis, Ore.

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

Megahan, W.F., and Nowlin, R.A. 1976. Sediment storage in channels draining small forested watersheds in the mountains of central Idaho. *In* Proceedings of the Third Federal Interagency Sedimentation Conference, 22–25 May 1976, Denver, Colo. Water Resources Council, Denver, Colo. pp. 115–126.

Montgomery, D.R. 1999. Process domains and the river continuum. J. Am. Water Resour. Assoc. **35**(2): 397–410.

Montgomery, D.R., and Foufoula-Georgiou, E. 1993. Channel network source representation using digital elevation models. Water Resour. Res. **29**(12): 3925–3934.

Murphy, M.L., and Koski, K.V. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North Am. J. Fish. Manage. **9**: 427–436.

Nierenberg, T.R., and Hibbs, D.E. 2000. A characterization of unmanaged riparian areas in the central Oregon Coast Range of western Oregon. For. Ecol. Manage. **129**: 195–206.

Pabst, R.J., and Spies, T.A. 1999. Structure and composition of unmanaged riparian forests in the coastal mountains of Oregon, U.S.A. Can. J. For. Res. **29**: 1557–1573.

Ralph, S.C., Poole, G.C., Conquest, L.L., and Naiman, R.J. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Can. J. Fish. Aquat. Sci. **51**: 37–51.

Reeves, G.H., Benda, L.E., Burnett, K.M., Bisson, P.A., and Sedell, J.R. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionary significant units of anadromous salmonids in the Pacific Northwest. Am. Fish. Soc. Symp. **17**: 334–349.

Shreve, R.L. 1969. Stream lengths and basin areas in topologically random channel networks. J. Geol. **77**: 397–414.

Soil Conservation Service. 1989. Soil survey of Coos County, Oregon. United States Department of Agriculture, Washington, D.C.

Strahler, A.N. 1964. Quantitative geomorphology of drainage basins and channel networks. *In* Handbook of applied hydrology. *Edited by* V.T. Chow. McGraw-Hill, New York. pp. 40–74.

Swanson, F.J., and Lienkaemper, G.W. 1978. Physical consequences of large organic debris in Pacific Northwest streams. USDA For. Serv. Gen. Tech. Rep. PNW-69.

Swanson, F.J., Fredricksen, R.L., and McCorison, F.M. 1982. Material transfer in a western Oregon forested watershed. *In* Analysis of coniferous forest ecosystems in the western United States. *Edited by* R.L. Edmonds. Hutchinson Ross, New York. pp. 233–266.

Van Sickle, J., and Gregory, S.V. 1990. Modeling inputs of large woody debris to streams from falling trees. Can. J. For. Res. **20**: 1593–1601.