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River Ecology and Management

Lessons from the Pacific Coastal Ecoregion

Sylvia Kantor
Associate and Managing Editor

With 202 Illustrations

1998

Springer -Verlag
New York, INC

13

Function and Distribution of Large Woody Debris

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Overview

- Wood is more abundant in streams in the Pacific coastal ecoregion than in streams anywhere else in North America. Abundance of large woody debris (LWD) decreases with increasing channel size. Size of large woody debris pieces increases with channel size.
- Input of large wood to stream channels occurs as a result of chronic bank cutting, windthrow, and stem suppression. Catastrophic occurrences, such as debris torrents, floods, and fires, can deposit large quantities of wood in channels in short periods of time.
- Large woody debris is removed from stream channels by leaching, microbial decomposition, fragmentation by invertebrates, physical fragmentation, and downstream transport. The relative importance of these processes varies with stream size.
- Large woody debris is a primary determinant of channel form in small streams, creating pools and waterfalls and affecting channel width and depth. Wood has less effect on channel form in larger streams.
- The presence of large woody debris facilitates deposition of sediment and the accumulation of finer organic matter. Dramatic increases in sediment and organic matter export occur immediately following removal or disturbance of LWD.
- Particulate organic matter accumulated by large woody debris is an important food source for many stream-dwelling invertebrates. Addition of wood to channels causes increased abundance of macroinvertebrates and changes species composition.
- Pools formed by large woody debris in streams are an important habitat for many species of stream fishes. Fish also use large woody debris as a source of cover.
- Sediment accumulated by woody debris provides a substrate for establishment of early-successional plant species. Large woody debris in riparian areas provides an important germination site for several conifer species.
- The quantity of woody debris in channels in the Pacific coastal ecoregion has decreased over time as a result of various land use practices including removal of wood from rivers for navigation and fish passage, splash damming, and clearing of riparian trees.

Introduction

Stream and river ecosystems are intricately interconnected physically, chemically, and biologically with the terrestrial ecosystems through which they flow. In the forested landscape of the Pacific coastal ecoregion, one of the most obvious indications of this connection is the great abundance of large woody debris (LWD) deposited in stream channels. LWD has a wide variety of influences on lotic ecosystems, dictating channel form, providing sites for storage of organic matter and sediment, and modifying the movement and transformation of nutrients (Bisson et al. 1987). The influence of wood on the structural and functional characteristics of streams affects the biological community (Bisson et al. 1987, Maser and Sedell 1994) including dynamics of riparian forest succession (Fetherston et al. 1995). Large wood on the riparian forest floor provides habitat for many species of wildlife (Bartels et al. 1985, Steel 1993). This chapter examines the spatial and temporal variability in LWD distribution and abundance through drainage networks, the processes of wood delivery and elimination, the influence of large wood on stream ecosystems, and the effect of land-use practices on LWD.

Abundance and Distribution of LWD in Channel Networks

Definitions of the size of LWD vary according to the objectives of a particular study. For example, investigators examining the contribution of LWD to the total organic matter load of a stream often include relatively fine material (as small as 2.5 cm in diameter) in their definition (Harmon et al. 1986). However, investigators examining the influence of wood on channel morphology often employ a much larger minimum size (usually 10 cm in diameter and 2 m in length) in their definition (Bilby and Ward 1989, Maser and Sedell 1994).

The use of multiple definitions of LWD makes comparisons of wood abundance among studies difficult. Nonetheless, research in the Pacific coastal ecoregion reveals general patterns of wood abundance (Table 13.1). Redwood (*Sequoia sempervirens*) forests of northern California exhibit the highest wood biomass with levels for some stream reaches as high as 180 kg/m^2, a value considerably greater than reported from any other region (Harmon et al. 1986). LWD biomass decreases in a northerly direction, with lowest levels observed in the sitka spruce forests of southeast Alaska. However, LWD abundance throughout the Pacific coastal ecoregion is much greater than that measured in other forested areas of North America (Harmon et al. 1986).

Amount and distribution of LWD in stream channels is strongly influenced by channel size (Figures 13.1 and 13.2) (Swanson et al. 1982, Bilby and Ward 1989). Small channels tend to contain abundant LWD that is distributed randomly. Wood is more easily transported in larger channels, leading to a reduction in the amount and aggregation of the remaining pieces. The size of these wood aggregations increases in a downstream direction while their frequency decreases (Swanson et al. 1982, Bisson et al. 1987). Despite the general tendency for wood abundance to decrease in larger channels, accumulations of LWD in large rivers

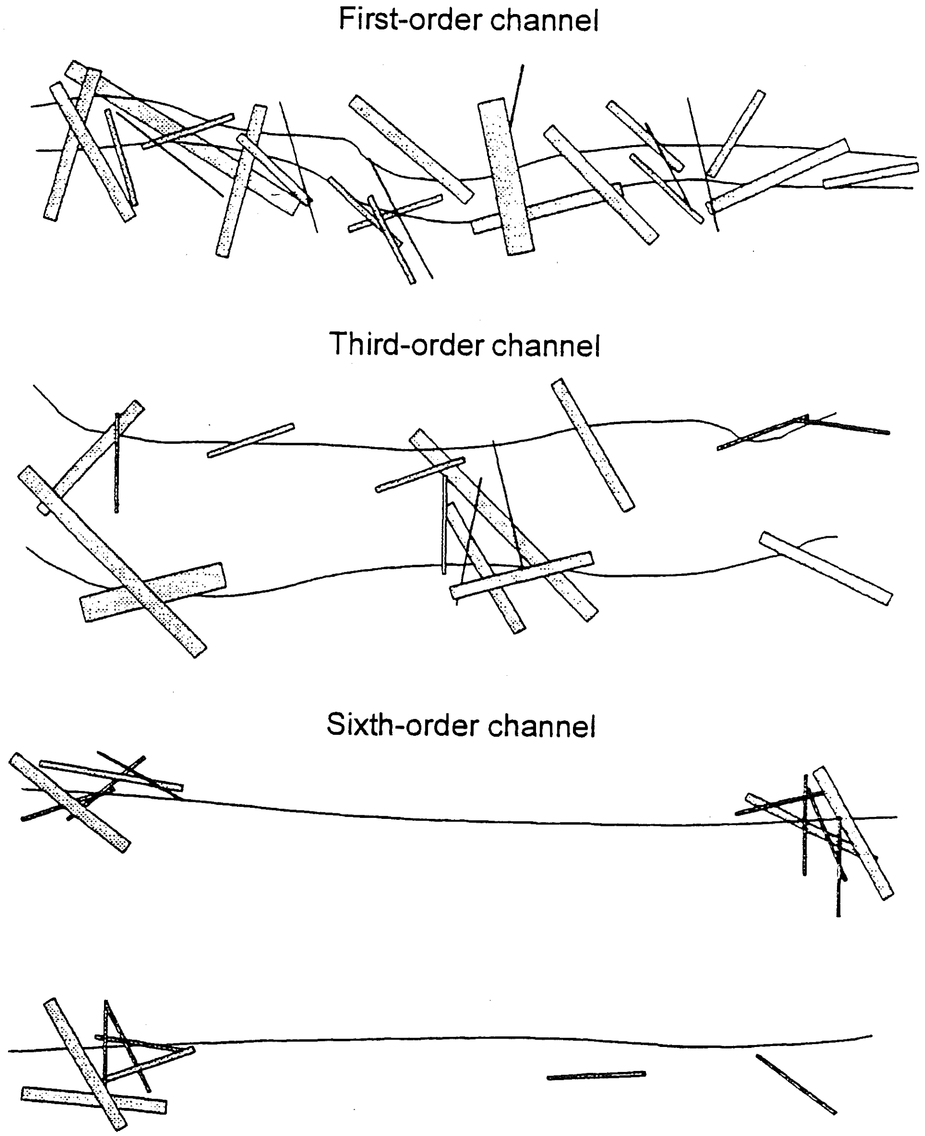
TABLE 13.1. Biomass of large woody debris in small streams (channel width <10 m) flowing through undisturbed, mature forests of the Pacific Coastal Ecoregion. Values from other areas in North America are shown for comparison.

Location	Primary tree species	Number of reaches inventoried	Average channel width (m)	LWD biomass (kg/m^2)
Northern Rocky Mountains, Idaho	Pine (*Pinus* spp.)	3	4.4	2.2
White Mountains, New Hampshire	Red spruce (*Picea rubens*), Eastern hemlock (*Tsuga canadensis*)	2	4.2	2.2
Northern Rocky Mountains, Idaho	Engelmann spruce (*Picea engelmanii*)	2	3.0	2.8
Smoky Mountains, Tennessee	Mixed hardwoods	5	5.1	5.0
Smoky Mountains, Tennessee	Red spruce, balsam fir (*Abies balsamea*)	2	4.8	7.2
Southeast Alaska	Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*)	4	3.5	6.6
Coastal British Columbia	Sitka spruce, western hemlock	5	—	31.6
Cascade Mountains, Oregon	Douglas-fir (*Pseudotsuga menziesii*)	24	3.5	34.7
Northern California	Coast redwood (*Sequoia sempervirens*)	8	6.8	74.2

Calculated from information presented in Harmon et al. (1986).

occasionally reach an enormous size. In the ninteenth century a wood jam on the Red River in Louisiana was estimated at 300 km in length (Lobeck 1939), and accumulations of several kilometers in length were reported on rivers along the Pacific coast of North America (Sedell and Luchessa 1982).

LWD amount and distribution also is affected by the density and species composition of the riparian forest. Tree density in riparian forests is positively related to LWD amount in streams in eastern Washington (Bilby and Wasserman 1989). LWD produced by conifers, which tends to be larger than that produced by hardwoods, is less likely to flush downstream, and significantly lower decay rates increase the longevity of LWD in the system (Harmon et al. 1986). Thus, streams flowing through mature stands of conifer in the Pacific Northwest tend to contain larger amounts of wood with larger average piece size than channels located in younger forests, which often are dominated by


First-order channel

Third-order channel

Sixth-order channel

FIGURE 13.1. Typical distribution of LWD in channels of various size. Aggregation of wood increases with channel size and total wood abundance decreases. This figure is based on maps of LWD in the McKenzie River basin, Oregon (Swanson et al. 1982).

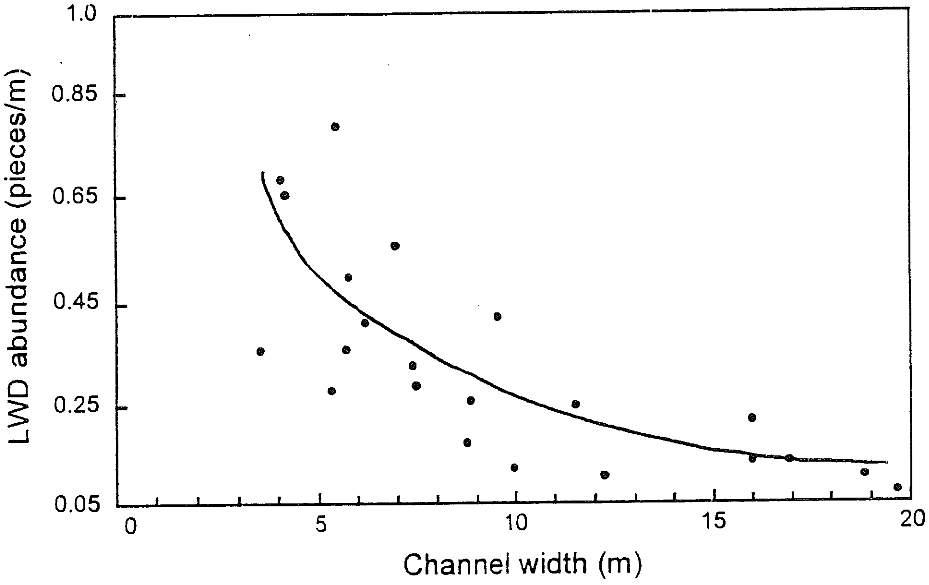


FIGURE 13.2. Abundance of LWD increases with decreasing channel size in old-growth forests in southwestern Washington (modified from Bilby and Ward 1989).

smaller, hardwood species (Grette 1985, Bilby and Ward 1991).

Channel type also is related to the abundance of LWD. Confined channels with boulder or bedrock substrate contain only about half the number of pieces of wood found in similarly sized, unconfined reaches with finer substrate (Bilby and Wasserman 1989). This difference is likely the result of an increased rate of LWD input to unconfined channels from bank cutting (Murphy and Koski 1989) and to the greater capacity for transporting wood downstream during high flow in the higher-energy, confined channels. Susceptibility of a watershed to catastrophic events, such as windstorms or landslides, also may significantly impact the amount of LWD in some stream channels (Keller and Swanson 1979, Bisson et al. 1987).

Stream size plays a major role in determining the size of LWD pieces retained in stream channels. Generally, the average size (diameter, length, or volume) of LWD in a stream channel increases with stream size (Figure 13.3) (Bilby and Ward 1989). The increase in LWD size is caused by the greater capacity for large channels to transport wood. Smaller pieces of wood are selectively flushed from larger channels leaving only larger pieces and causing a decrease in wood amount but an increase in average piece size.

Processes Controlling Input and Output of LWD

Input processes. Both chronic and episodic processes are responsible for delivering LWD to streams (Figure 13.4) (Keller and Swanson 1979, Bisson et al. 1987). Chronic mechanisms include the regular introduction of wood as a result of tree mortality or gradual bank undercutting. These processes tend to add small amounts of wood at frequent intervals. Much of the LWD in unconfined channels is introduced by undercutting of trees on the bank (Grette, 1985, Murphy and Koski, 1989), whereas windthrow is the principal mechanism of wood delivery to channels with confined, erosion-resistant banks (Lienkaemper and Swanson 1987).

The rate at which these chronic input processes deliver LWD to a channel varies as a

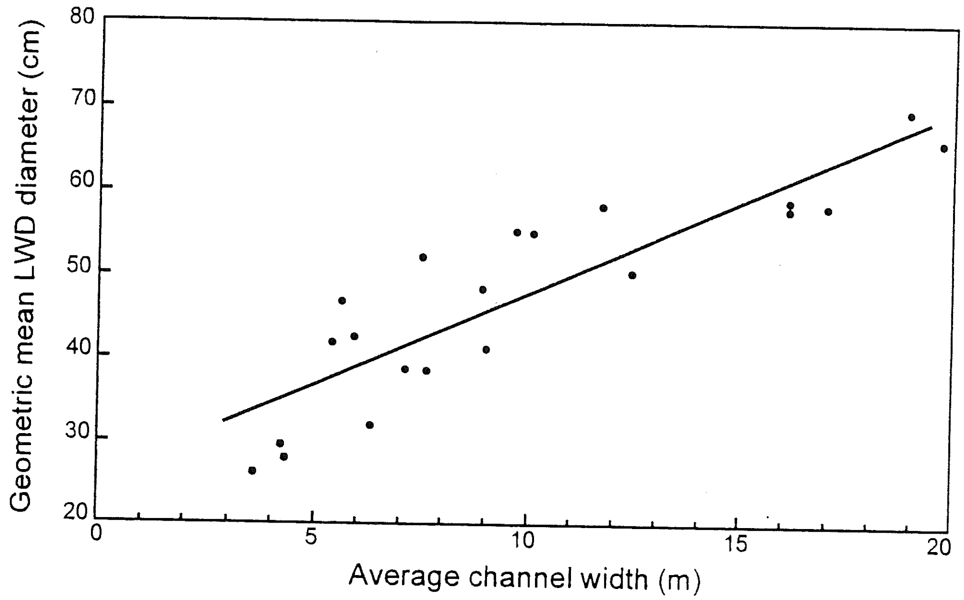


FIGURE 13.3. Relationship between channel width and geometric mean diameter of pieces of LWD for channels in old-growth forests in southwestern Washington (modified from Bilby and Ward 1989).

function of successional stage of the riparian stand. Red alder (*Alnus rubra*), a common early-successional species in riparian areas in the Pacific coastal ecoregion, has a relatively short life span and begins to die and contribute LWD to the channel approximately 60 years after stand establishment (Grette 1985). Shade-tolerant conifers, such as western redcedar

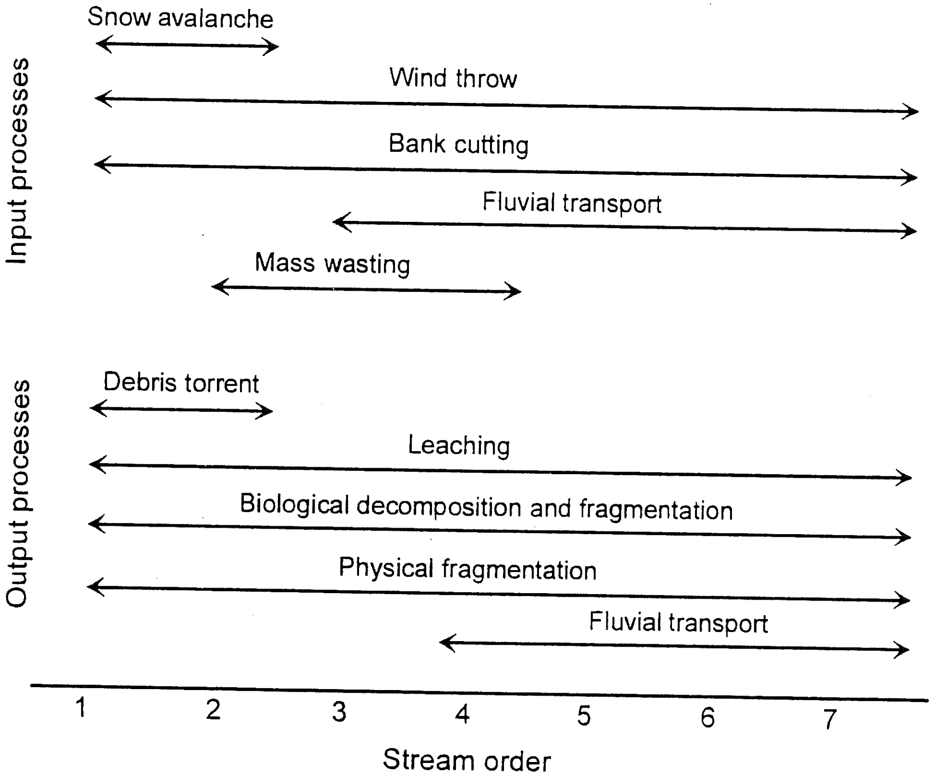


FIGURE 13.4. Processes of wood input and output to channels in the Pacific coastal ecoregion. Different processes predominate in different sized channels (modified from Keller and Swanson 1979).

(*Thuja plicata*) or western hemlock (*Tsuga heterophylla*), establish in the alder understory, then occupy the site and contribute wood to the channel as a result of stem suppression (mortality due to competition). Evidence suggests that stem suppression is the major process contributing LWD to stream channels in the western Cascade Mountains of Washington in stands up to 300 years old (Rot 1995). In stands older than this, mortality of dominant trees due to disease and windthrow is the primary process delivering wood to channels.

The length of time it takes (following a vegetation-removing disturbance) for a riparian area to produce woody debris large enough to remain in the channel varies with stream size. In large channels, input of LWD takes longer to resume and the rate of LWD accrual is slower following a severe disturbance (Bilby and Ward 1991). For example, in 3rd-order channels on the Olympic Peninsula, measurable contributions of wood from disturbed riparian areas did not occur until 60 years after harvest (Grette 1985). Bilby and Wasserman (1989) suggest that streamside vegetation in southwestern Washington must be at least 70 years old to provide stable material to streams more than 15 m wide.

Episodic input events, including catastrophic windthrow, fire, or severe floods, occur infrequently but can add massive amounts of wood to the channel network in a very short period of time. Landslides and debris torrents can transport huge amounts of wood from hillslopes and headwater tributary channels to downstream reaches (Keller and Swanson 1979). Input by this mechanism, however, is restricted to lower-order channels in steep terrain, where landslides are common (Figure 13.4) (Swanson et al. 1987). Infrequent, severe windstorms in the Pacific coastal ecoregion have been responsible for leveling very large areas of forest (Harmon et al. 1986). A single windstorm on October 12, 1962, blew down $2.6 \times 10^7 m^3$ of wood (Orr 1963). Fire occurrence varies as a function of aspect, elevation, and other factors. However, fires recur in most Pacific coastal forests at intervals of 200 to 1,000 years, often resulting in the delivery of large amounts of LWD to stream channels (Agee 1988). Very severe floods also add large amounts of wood to channels through accelerated bank cutting and transport of wood stored on the floodplain into the channel (Keller and Swanson 1979). Input of LWD by flooding tends to be particularly prevalent in large channels with extensive floodplains.

The area from which LWD is supplied to the channel varies as a function of the species composition and age of the riparian vegetation, topography of the streamside area, characteristics of the channel, and direction of the prevailing wind (Steinblums et al. 1984, Grette 1985, Murphy and Koski 1989, McDade et al. 1990). Both empirical and theoretical analyses of the probability of input of LWD to a channel as a function of distance from the streambank have been developed (Murphy and Koski 1989, McDade et al. 1990, Robison and Beschta 1990b, Van Sickle and Gregory 1990, Lorenzen et al. 1994). In general, these analyses suggest that the primary zone of input is equivalent to the height of the tallest trees growing along the stream. The probability of a tree within the riparian zone entering the stream when it falls decreases with distance from the channel edge and varies due to differences in tree height, a function of stand age and tree species (Figure 13.5) (McDade et al. 1990, Van Sickle and Gregory 1990). In general, 70 to 90% of the input of LWD occurs within 30 m of the channel edge. However, trees growing anywhere on the floodplain of an unconfined reach may ultimately be captured by the stream due to lateral migration of the channel across the valley bottom.

Output processes. Leaching, fragmentation, microbial decay, invertebrate consumption, and fluvial transport all contribute to the ultimate demise of a piece of wood in a stream (Figure 13.4) (Keller and Swanson 1979). However, because wood is resistant to solution, leaching, the gradual dissolution of the wood by water, plays a minor role in LWD decomposition (Harmon et al. 1986).

Fragmentation, the physical breakdown of the wood by the force of flowing water, is one of the principal means of wood degradation in streams (Aumen 1985). The process of fragmentation is accelerated by microbial decay,

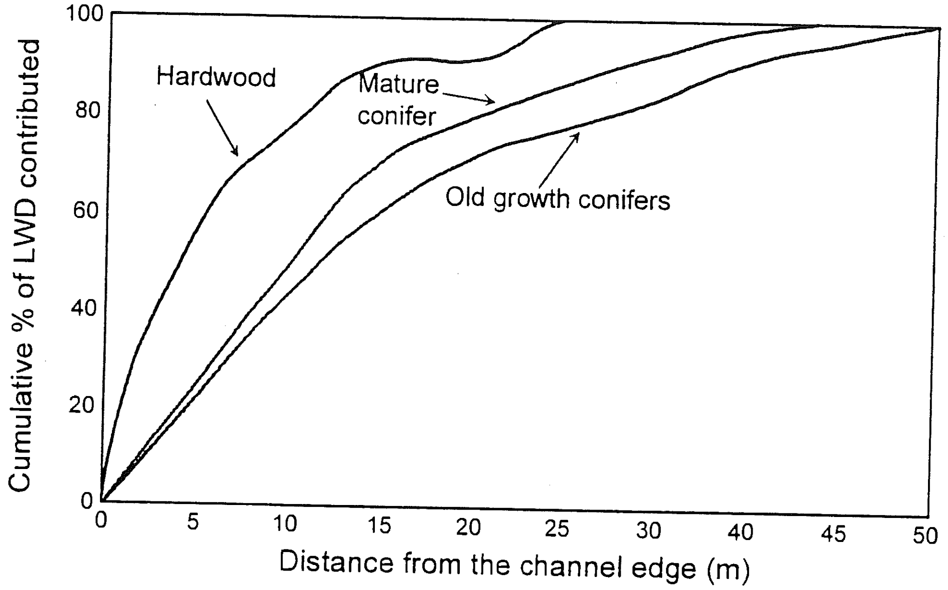


FIGURE 13.5. The cumulative proportion of LWD delivered to a stream as a function of distance from the channel edge. Differences in tree height between hardwood trees, mature conifers and old-growth conifers are indicated by the three curves (modified from McDade et al. 1990).

which weakens the wood. Microbial decay of wood in streams is conducted primarily by bacteria (Crawford and Sutherland 1979) and occurs in a thin layer on the wood surface (Aumen 1985). Decomposition by fungi, the primary organisms responsible for wood decay in terrestrial environments, is limited in streams because of the high water content and low oxygen levels within the wood (Savory 1954). Invertebrates that feed on wood accelerate the decomposition process by fragmenting the wood and providing fresh surfaces for microbial colonization. However, these highly specialized invertebrates generally consume relatively small amounts of wood and have a minor impact on decomposition rate (Wallace and Anderson 1996).

The importance of downstream transport as a process of wood removal from streams varies with channel size. In small, steep headwater tributaries, debris torrents can remove wood from long stretches of stream channels, depositing this material in a large accumulation at the terminus of the torrent (Swanson et al. 1976). Downstream transport of wood during periods of elevated flow is a process which is most common in larger channels (Keller and Swanson 1979).

LWD in Pacific coastal streams can persist for a very long time (Franklin et al. 1981). A study using dendrochronological methods identified pieces of wood that had remained for up to 108 years in streams in the Cascade Mountains of Oregon (Swanson and Lienkaemper 1978). Size and species of logs (mean piece volume = 1.6 m^3) in streams on Washington's Olympic Peninsula decayed at the rate of 1%/yr, with large pieces persisting longer than small pieces (Grette 1985). In southeast Alaska, pieces 10 to 30 cm in diameter never persisted for more than 110 years, whereas pieces greater than 60 cm in diameter persisted up to 226 years (Murphy and Koski 1989). The rate of LWD depletion in this study was higher in tightly constrained, high-energy channels than it was in low-gradient systems with broad floodplains. A study in the Cascade Mountains of Oregon indicated that western redcedar decayed most slowly, followed in order by Douglas-fir (*Pseudotsuga menziesii*), western hemlock, and red alder (Swanson and Lienkaemper 1978). Rates of microbial respiration on LWD in stream channels suggest that total decomposition requires from 5 to 200 years, depending on piece size (Anderson et al. 1978).

LWD Function in Stream Ecosystems

Channel form. Large wood has a major impact on channel form in 1st- through 4th-order streams in the Pacific coastal ecoregion. Wood tends to increase average channel width and increase variability in width (Zimmerman et al. 1967, Trotter 1990). In several small streams in northern California, channel width near large accumulations of LWD were 27 to 124% greater than average channel width of the reach (Keller and Swanson 1979). LWD also forms and stabilizes gravel bars and other depositional sites (Lisle 1986, Abee and Montgomery 1995, Fetherston et al. 1995), forms waterfalls (Heede 1972), creates pools (Robison and Beschta 1990a) and influences channel meandering and bank stability (Swanson and Lienkaemper 1978, Cherry and Beschta 1989). Although LWD tends to influence the channel form of larger systems less, occasional large LWD accumulations may increase channel width, create bars and other depositional features, and encourage the development of meander cutoffs (Keller and Swanson 1979).

Wood is often the primary agent forming pools in plane-bedded and step-pool channels and plays a role in forming or modifying pools in other channel types as well (Montgomery and Buffington 1993, definition of channel types in Chapter 2 of this volume). In small, high-gradient, stepped-pool channels, wood forms a waterfall by obstructing flow and creates a plunge pool. Obstructions other than wood may form waterfalls in these small channels, but wood is most often responsible (Keller and Swanson 1979, Bilby and Ward 1991). LWD forms pools by concentrating flow and scouring the bed in larger, lower-gradient, plane-bedded channels. In such channels, pools are infrequent when LWD is rare. Over 80% of the pools in a small stream in southwest Washington are associated with wood (Bilby 1984). Similarly, 80% of the pools in a series of small streams in the Idaho panhandle are associated with wood (Sedell et al. 1985), and 86% of the pools in a northern California stream are associated with large roughness elements, the majority of which are LWD (Lisle and Kelsey 1982). The proportion of stream surface area occupied by pools range from 4 to 11% for several small streams in British Columbia with little LWD; pools in nearby reaches with abundant wood occupy from 27 to 45% of the surface area (Fausch and Northcote 1992).

The relative importance of LWD in pool formation decreases with increasing channel size and decreasing gradient (Bilby and Ward 1989, Montgomery and Buffington 1993, Chapter 2 this volume). Pool formation is primarily dictated by dynamics of flow in channels exhibiting a pool-riffle morphology, rather than by channel obstructions like large woody debris. However, channel-spanning accumulations of wood occasionally form even in large rivers and can create lake-like conditions upstream (Sedell and Luchessa 1982). In addition, LWD forms pools along the channel margins or in secondary channels of large rivers, which can provide important habitat for some species of fish (Bisson et al. 1987).

Pieces of LWD associated with large accumulations of finer organic matter (e.g., twigs, needles, leaves) are more likely to form pools than individual pieces. Bilby and Ward (1991) found that 77% of the pieces of LWD with fine debris accumulations greater than $0.5\,m^3$ formed pools compared with 26% of LWD pieces with accumulations less than $0.5\,m^3$.

LWD influences pool size as well as pool frequency. The deepest pools tend to be associated with large roughness elements, like LWD (Lisle and Kelsey 1982). Average pool depth decreased following experimental removal of wood from several stream reaches in the area impacted by the 1980 eruption of Mt. St. Helens (Lisle 1995). Depth and sinuosity in several reaches of a small British Columbia stream with abundant LWD was greater than in nearby reaches which lacked wood (Fausch and Northcote 1992). Surface area of LWD-formed pools is positively correlated with the size of piece of wood, or wood accumulation, forming that pool (Bilby and Ward 1989). The effect of piece size on pool surface area can be quite dramatic. For example, based on the relationships in Bilby and Ward (1989), a piece of LWD

30 cm in diameter and 5 m in length in a stream with a channel width of 8 m would produce a pool with a surface area of $1.4\,m^2$. A piece of LWD 60 cm in diameter and 5 m in length would produce a pool with a surface area of $3.9\,m^2$.

Wood also affects channel form through the creation of waterfalls. Waterfalls form plunge pools and influence sediment transport in streams. The greater the proportion of the drop in elevation of a stream caused by waterfalls, the less efficient the system is at moving sediment downstream (Heede 1972). The proportion of channel drop accounted for by summing the heights of waterfalls caused by LWD ranged from 30 to 80% in streams in the western Oregon Cascades (Keller and Swanson 1979) and 6% in a stream in the Oregon Coast Range (Marston 1982). The proportion of elevation drop caused by LWD decreased with increasing stream size for 22 stream reaches in areas of old-growth forest in western Washington, ranging from greater than 15% in channels less than 10 m wide to less than 5% for channels 10 to 20 m wide (Bilby and Ward 1989). In channels wider than 20 m, waterfalls formed by LWD are very rare.

Movement of particulate matter. LWD controls routing of sediment and particulate organic matter through channel networks by creating areas of low flow velocity and shear stress where this material can be stored. The primary method by which LWD decreases shear stress in small, high-gradient streams is through the formation of step-pools that produce a depositional site upstream from the waterfall and along the margins of the plunge pool (Heede 1972, Montgomery and Buffington 1993, Chapter 2 this volume). In larger systems, areas of reduced shear stress form downstream from the wood accumulation or between the LWD and the stream bank (Keller and Swanson 1979, Lisle 1986).

Depositional sites associated with LWD tend to be small but frequent in small streams, In channels less than 7 m wide flowing through old-growth forest in western Washington, 39% of the LWD pieces were associated with sites of sediment deposition (Bilby and Ward 1989). The frequency with which LWD formed depositional sites decreased with increasing stream size, with 26% of the pieces accumulating sediment in channels 7 to 10 m wide and 19% in channels over 10 m wide. The proportion of the channel covered by sediment associated with LWD decreased with increasing stream size as well. Depositional sites formed by LWD covered 19% of the streambed in channels 5 m wide, decreasing to 3% in channels 15 m wide. The decrease was due to a reduction in the amount of LWD and in the proportion of LWD pieces forming depositional areas.

The average size of depositional sites increases with channel size (Bilby and Ward 1989). This is, in part, the result of the steep banks, high gradient, and step-pool morphology of small streams, which tend to limit the size of depositional areas relative to those formed downstream from LWD accumulations in channels with a pool-riffle or plane-bed morphology (Montgomery and Buffington 1993). In addition, larger pieces or accumulations of LWD create larger depositional areas, and average piece size and frequency of large aggregations of LWD increases with channel size (Bilby and Ward 1991).

LWD may form very large mid-channel or channel-margin gravel bars in large channels (Abee and Montgomery 1995, Fetherston et al. 1995, Chapter 12 this volume). These gravel bars frequently increase in size over time as additional LWD is accumulated at the upstream edge of the bar. Establishment of vegetation further stabilizes the bar and encourages additional deposition. Ultimately, a vegetative community becomes established that is oldest at the upper middle point of the bar and decreases in age towards the margins.

The influence of LWD on sediment routing can be demonstrated by determining the proportion of stored sediment associated with wood in a stream reach and by measuring sediment transport before and after LWD removal. Wood was responsible for the storage of 49% of the sediment in seven, small, Idaho watersheds (Megahan 1982) and 87% of the sediment in the channel of a small stream in New Hampshire (Bilby 1981). Removal of wood from a 250 m reach of a stream in the Oregon

Coast Range released 5250 m^3 of sediment (Beschta 1979). The winter following the removal of redwood LWD from a 100 m reach of a northern California stream 60% of the stored sediment was exported (MacDonald and Keller 1983). Experimental removal of LWD from a 175-m reach of a 2nd-order channel in New Hampshire led to a doubling in the rate of particulate matter export from the entire watershed the following year (Bilby 1981).

Wood in streams is responsible for storing large amounts of particulate organic matter, such as leaves, needles, or twigs. Naiman and Sedell (1979) found that amount of particulate organic matter (<10 cm) was strongly related to abundance of LWD in reaches of the McKenzie River watershed in western Oregon (Figure 13.6). Trotter (1990) found that the presence of LWD in three stream reaches more than doubled the amount of stored coarse particulate organic matter. LWD was responsible for storing 75% of the organic matter in 1st-order channels and 58% in 2nd-order channels in the White Mountains of New Hampshire (Bilby and Likens 1980). Removal of LWD from a 175 m-reach of 2nd-order channel increased export of coarse particulate organic matter (>1 mm) 138% and fine particulate organic matter (<1 mm) 632% (Bilby and Likens 1980), whereas, addition of LWD to three stream reaches in the southern Appalachian Mountains led to an increase in stored particulate organic matter from 88 to 1,568 g/m^2 (Wallace et al. 1995). In the absence of LWD, much of the terrestrial organic matter entering streams is flushed rapidly downstream (Naiman and Sedell 1980). Reduced quantities of particulate organic matter decrease the productivity and change the composition of the macroinvertebrate community (Wallace et al. 1995, Chapter 8 this volume).

An important source of particulate organic matter in Pacific coastal ecoregion streams are Pacific salmon (*Oncorhynchus* spp.), which die after spawning. Monitoring of several hundred, tagged coho salmon (*O. kisutch*) carcasses in a number of western Washington streams revealed that 60% were retained by LWD (Cederholm et al. 1989). Materials transported to freshwater by spawning salmon makes a substantial contribution to the productivity of the typically, oligotrophic systems in this region.

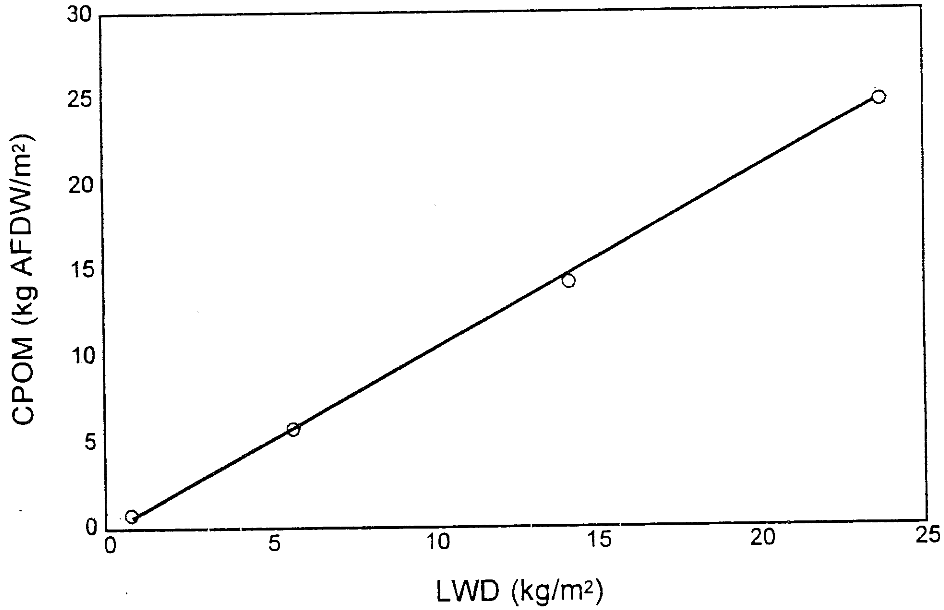


FIGURE 13.6. The relationship between large woody debris (LWD) and coarse particulate organic matter (CPOM) in channels within the McKenzie River watershed in Oregon. LWD is defined as larger than 10 cm and CPOM as smaller than 10 cm. Data from Naiman and Sedell (1979). Regression equation: CPOM Amount = 1.04 (LWD Amount) − 0.13; $r^2 = 0.99$.

Kline et al. (1990 1994) found that spawning pink salmon (*O. gorbuscha*) and sockeye salmon (*O. nerka*) were the source of most nitrogen (N) in the tissues of invertebrates and juvenile fishes in two Alaskan watersheds. Twenty-five to 40% of the N and carbon (C) in the tissues of juvenile salmonid fishes in a small stream in western Washington were derived from spawning coho salmon (Bilby et al. 1996). Salmon carcasses also are an important food resource for many species of wildlife (Cederholm et al. 1989). Availability of this material is reduced in stream reaches containing little LWD.

By controlling the rate of particulate matter transport in channels, LWD influences the rate of movement of nutrients through drainage systems. Export of elements contained in particulate matter increased as much as 88-fold following removal of wood from a short stretch of stream channel in New Hampshire (Table 13.2) (Bilby 1981).

Transport of dissolved matter, however, is less impacted by LWD. Dissolved organic carbon concentration increased after removal of the wood from a stream reach in New Hampshire, but the concentration of 10 ions did not change (Bilby 1981). Nonetheless, LWD can influence the movement of dissolved nutrients by affecting the rate at which these materials are removed from stream water. Addition of logs to a stream in North Carolina slightly decreased uptake rate for ammonium while nitrate uptake rate increased (Wallace et al. 1995). However, the uptake rate of phosphate was not affected by the addition of logs.

Water quality. Low oxygen concentrations in stream water as a result of decomposition of LWD seldom occurs in streams because wood has a very low surface area to volume ratio that minimizes the area available for microbial activity. In addition, wood is composed of material relatively resistant to decomposition, thus the rate of oxygen consumption by decomposing organisms on wood is low (Harmon et al. 1986), and the rapid, turbulent flow of the water helps facilitate reoxygenation from the atmosphere (Ice 1978). However, introduction of large amounts of woody debris to beaver ponds or to slowly flowing streams during logging can cause decreases in oxygen concentration below levels needed to support salmonid fishes (Hall and Lantz 1969).

TABLE 13.2. The estimated export of various elements from a 175-m reach of a 2nd-order stream in the White Mountains of New Hampshire. Relationships between dissolved and particulate matter export and discharge were developed before and after removal of LWD. Values presented represent estimates derived by applying the relationships to daily discharges during a single year.

Element	Export with LWD (kg/y)	Export without LWD (kg/y)	Increase without LWD (%)
Si (silicon)	710	2,350	231
Al (aluminum)	84.7	554	554
Fe (iron)	32.5	213	555
Ca (calcium)	275	331	20
Na (sodium)	152	225	48
K (potassium)	63.3	212	235
Mg (magnesium)	66.5	110	65
Mn (manganese)	1.1	7.0	536
P (phosphorus)	1.1	5.3	382
S (sulfur)	389	392	0.8
C (carbon)	791	1,940	145
N (nitrogen)	57.5	72.7	26
Total Export	5,510	13,440	144

Modified from Bilby 1981.

Three common tree species in the Pacific coastal ecoregion, western redcedar, western hemlock, and sitka spruce (*Picea sitchensis*), produce leachate toxic to aquatic organisms (Buchanan et al. 1976). The toxicity of leachates from wood is exacerbated by their tendency to reduce streamwater pH (Allee and Smith 1974). Under most conditions, however, leaching of materials from wood occurs at a very slow rate, keeping concentrations well below toxic levels (Bisson et al. 1987). Impacts have been noted only where large quantities of woody material are introduced into small, slowly flowing streams during logging. Leachate from LWD appears to be more toxic to salmonid fishes than aquatic insects (Peters et al. 1976) with eggs and fry particularly susceptible (Buchanan et al. 1976).

Macroinvertebrates. LWD is directly utilized by macroinvertebrates in streams as substrate and a source of food (Table 13.3). In addition, the role wood plays in accumulating organic matter and sediment creates habitats favored by certain types of aquatic invertebrates that may be rare elsewhere in the channel. Over 50 taxa of macroinvertebrates in five orders are closely associated with wood (Dudley and Anderson 1982).

Coarse particulate organic matter is the primary food source for shredding macroinvertebrates, and these organisms process coarse material into finer particles that are used by collector/gather macroinvertebrates (Merritt and Cummins 1978). As indicated in the previous section, coarse particulate organic matter availability is greatly reduced in the absence of LWD. Productivity, abundance, and biomass of macroinvertebrates tends to be greatest in areas of high particulate organic matter availability (Gurtz and Wallace 1984, Huryn and Wallace 1987, Smock et al. 1989, Richardson 1991). This has been demonstrated by the addition of LWD to a southern Appalachian stream which resulted in a 24-fold increase in invertebrates and a 2.1-fold increase in biomass at the location where wood was placed (Figure 13.7) (Wallace et al. 1995).

LWD influences invertebrate community composition as well as overall abundance. Wallace et al. (1995), found that addition of LWD to a small stream caused increases in certain taxa and functional feeding groups (Diptera, especially chironomids, and noninsect invertebrates) and decreases in others (Ephemeroptera) (Figure 13.7). Biomass of collectors and predators increased while that of scrapers and filterers decreased. Reductions in scrapers was attributed to a lack of suitable substrate caused by deposition of fine organic matter and sediment near the wood. Reduced availability of suspended organic matter caused by decreased current velocities near the added LWD accounted for declines in filterers.

TABLE 13.3. Various uses of LWD by orders of freshwater insects.

Type of wood utilization	Orders of invertebrates
Ingestion	Coleoptera, Plecoptera, Trichoptera, Diptera
Oviposition site	Trichoptera, Hemiptera, Diptera
Burrowing during rearing	Coleoptera, Ephemeroptera
Attachment to surface during rearing	Coleoptera, Diptera, Trichoptera, Ephemeroptera
Pupation site	Trichoptera, Diptera

Summarized from information presented by Harmon et al. (1986).

There are a number of invertebrates that live or feed on wood and the microflora it supports. Several genera of elmid beetles are known to ingest wood (White 1982); *Lara avara* apparently feeds only on this material (Anderson et al. 1978). The stable substrate provided by the wood is important for species which cannot tolerate a frequently shifting bottom, such as filter-feeding insects (Cudney and Wallace 1980). A majority of the insect productivity may be associated with LWD in these soft-bottomed systems. Biomass of insects on wood in a southeastern United States stream was 5 to 10 times that on the sand of the streambed (Benke et al. 1984).

Marine invertebrates also use wood that has been transported to estuaries and the ocean by streams and rivers. LWD in estuaries and the ocean provides a stable substrate for attachment for numerous sessile invertebrates and serves as a food source for shipworms and other wood-boring marine organisms (Maser and Sedell 1994). Experimental addition of wood to an estuary resulted in increased densities of three crustaceans: grass shrimp (*Palaemonetes pugio*), blue crab (*Callinectes sapidus*), and mud crab (*Rhithropanopeus harrisii*) (Everett and Ruiz 1993).

Fish. Much of the work on the role of woody debris as habitat and cover for fish has focused on salmonids in Pacific Northwest streams (Sedell et al. 1984, Murphy et al. 1985, Fausch and Northcote 1992). Juvenile coho salmon and older age classes of cutthroat trout (*O. clarki*) and steelhead (*O. mykiss*) prefer the pool habitat created by LWD over faster-water habitat types (Bisson et al. 1982). Pools provide a location where fish can maintain their position with a minimum of effort, yet food items

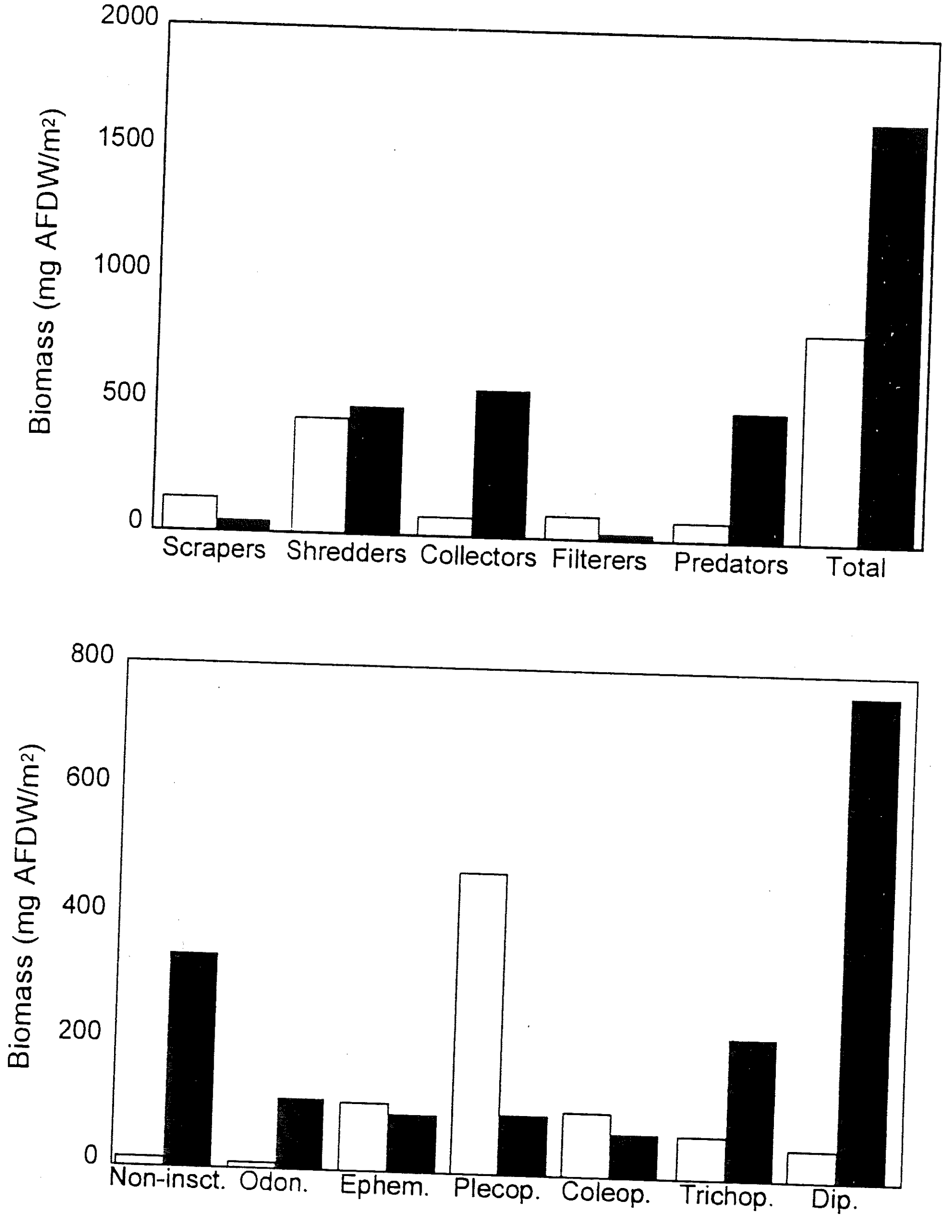


FIGURE 13.7. Biomass of invertebrates at channel cross sections with LWD ■ and without LWD □ in a southern Appalachian stream. The upper panel segregates organisms by functional category, the lower panel by taxonomic category. Taxonomic abbreviations are: Non-insct. = invertebrates other than insects; Odon. = Odonata; Ephem. = Ephemeroptera; Plecop. = Plecoptera; Coleop. = Coleoptera; Trichop. = Trichoptera; Dip. = Diptera (data from Wallace et al. 1995).

carried by the current are abundant (Dill et al. 1981, Fausch 1984). In faster water, food availability may be high but the metabolic cost of maintaining position can negate this advantage.

Fish populations are typically larger in streams with plenty of LWD than in systems with little wood. Stream reaches with large amounts of wood in southern British Columbia supported standing stocks of juvenile coho and cutthroat trout five times higher than reaches in the same system with little wood (Figure 13.8) (Fausch and Northcote 1992). Comparison of winter population levels of juvenile coho in 54 stream reaches in southeast Alaska revealed that average coho salmon density in streams with wood volume less than 50 m^3 per 30-m stream section was only 25% the average density in streams with greater wood volumes (Murphy et al. 1985). Decreases in fish abundance have been documented following wood removal from channels throughout the Pacific Northwest (Lestelle 1978, Bryant 1983, Dolloff 1986, Elliott 1986). Deliberate additions of LWD to streams resulted in increased abundance of juvenile salmonids in streams on the coast of Oregon (House and Boehne 1986) and British Columbia (Ward and Slaney 1979). An increase in the abundance of adult coho salmon was attributed to increased wood in a coastal Oregon stream, presumably due to improved survival of the juvenile fish (Crispin et al. 1993). In high-gradient streams on the Oregon coast, loss of wood and associated pools led to a decrease in coho salmon (Reeves et al. 1993). Loss of wood in low-gradient channels led to a decrease in the abundance of cutthroat trout due to a decrease in the number of deep pools preferred by older cutthroat and a reduction in structurally complex habitat that would enable juvenile trout to compete successfully with the larger, juvenile coho salmon.

More complex wood structures, such as rootwads or accumulations of multiple pieces, tend to attract more fish than single logs (Sedell et al. 1984). In Kloiya Creek, British Columbia, 99% of the coho salmon fry and 83% of the steelhead parr were associated with rootwads placed in the mid-channel area of the stream, where cover had previously been scarce (Shirvell 1990). Examination of the propensity for juvenile coho salmon to leave experimental channels with varying conditions of shade, flow velocity, and woody cover indicated that woody cover was the most important factor in promoting continued residence during high flows (McMahon and Hartman 1989).

Large accumulations of wood may block the passage of anadromous fishes. For many years this was perceived as a serious problem and wood was removed from channels in order to prevent blockages (Merrell 1951). However, many LWD accumulations which may be blocks at low flows are passable at higher discharges. In addition, these blocks normally occur in steeper channels where habitat available for spawning and rearing by anadromous fish is often limited. It is estimated that, historically, only 5 to 20% of available anadromous fish habitat was inaccessible because of natural blockages formed by LWD (Sedell et al. 1984).

Some marine fishes also are attracted to LWD. Addition of wood to an estuary caused increased abundance of several species of fishes (Everett and Ruiz 1993). The wood created conditions which increased invertebrate populations, the primary food source for the fish,

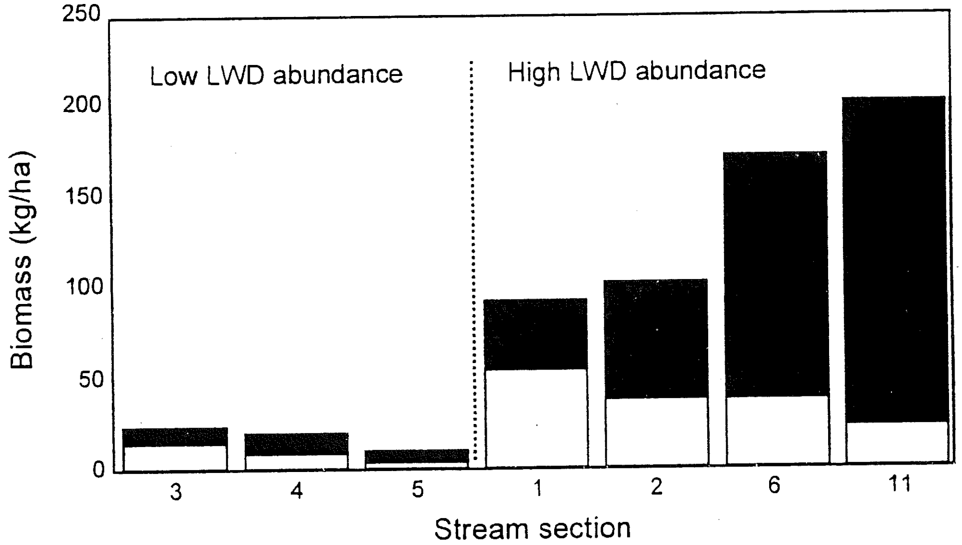


FIGURE 13.8. Biomass of juvenile coho salmon ☐ and cutthroat trout ■ in southern British Columbia stream reaches with little LWD and abundant LWD (data from Fausch and Northcote 1992).

and provided cover. Floating wood is utilized by pelagic, ocean fishes for cover and shade (Maser and Sedell 1994), and smaller fishes and other organisms attracted to wood are eaten by larger fish. This association is appreciated by commercial fishermen. Purse-seining beneath driftwood is a common method of fishing for tuna (Thunnidae).

Riparian successional processes. The highly diverse vegetation supported by riparian areas in the Pacific Northwest (Campbell and Franklin 1979, Pollock 1995) is the product of small-scale spatial heterogeneity of environmental conditions and frequent disturbance. The physical characteristics and vegetation of the streamside area differ from those upslope as a result of interactions with the stream, including frequent inundation, saturated soils, and physical disturbance of the streamside vegetation due to flood flows, mass soil movements or ice damage (Agee 1988). LWD also contributes to the spatial heterogeneity in riparian areas. Woody material in the channel or within the riparian area creates sites where sediment and organic matter transported by the stream collects. These depositional sites provide locations for the establishment of pioneer plant species, commencing the successional process (Fetherston et al. 1995). Ultimately, patches of vegetation established by this process may be removed during a disturbance event, delivering LWD to the channel and reinitiating the process. Even in old-growth forests, a substantial proportion of the riparian area supports vegetation normally associated with early successional conditions (Rot 1995).

The role of LWD in creating depositional sites suitable for occupation by plants is influenced by topography of the site, size of the channel, and the types of disturbance to which the channel is susceptible (Fetherston et al. 1995). Smaller streams in mountainous terrain have steep channel gradients and stream banks, which limit the size of depositional sites created by LWD (Bilby and Ward 1989). These channels also are more prone to avalanches and debris flows, events which often remove vegetation and much of the soil from riparian areas. As a result, the vegetative communities established on these sites tend to be short-lived. In contrast, the lack of confinement, low gradients, and extensive floodplains associated with larger rivers provide conditions where LWD accumulations can form large depositional areas which are less frequently influenced by disturbance events which remove vegetation.

Some common conifer species in Pacific Northwest forests germinate on decomposing, downed logs, commonly referred to as nurse logs (Harmon et al. 1986). Eighty percent of the conifer regeneration in riparian areas in the Oregon Coast Range occurs on woody debris (Thomas et al. 1993). More than 90% of the conifer regeneration occurred on decomposing logs on floodplain terraces adjacent to the Hoh River in Washington (McKee et al. 1984). Nurse logs elevate the seedlings, which reduces competition with other plants and provides lower soil moisture, enabling establishment of species which cannot tolerate extended periods of soil saturation.

Influence of Land Use on LWD

A variety of land use practices employed in the Pacific coastal ecoregion over the last century have altered the amount and characteristics of large wood in streams. Removal of wood accumulations in large rivers began in the nineteenth century to improve navigation and enable logs from upstream forests to be floated to downstream mills (Sedell and Luchessa 1982). The practice of splash damming was developed to move logs to watercourses large enough to allow them to be floated to the mills. This practice entailed the construction of dams on relatively small streams. Cut timber was placed in the pond formed by the dam and in the channel below the dam. The impounded water was then released, carrying the logs downstream on the crest of the resultant flood. Over 70 splash dams were operated in streams draining to Grays Harbor and Willapa Bay in southwestern Washington during the early part of the twentieth century (Figure 13.9) (Wendler and Deschamps 1955), and the practice was common throughout the Pacific coastal ecoregion (Sedell and Luchessa 1982). Trans-

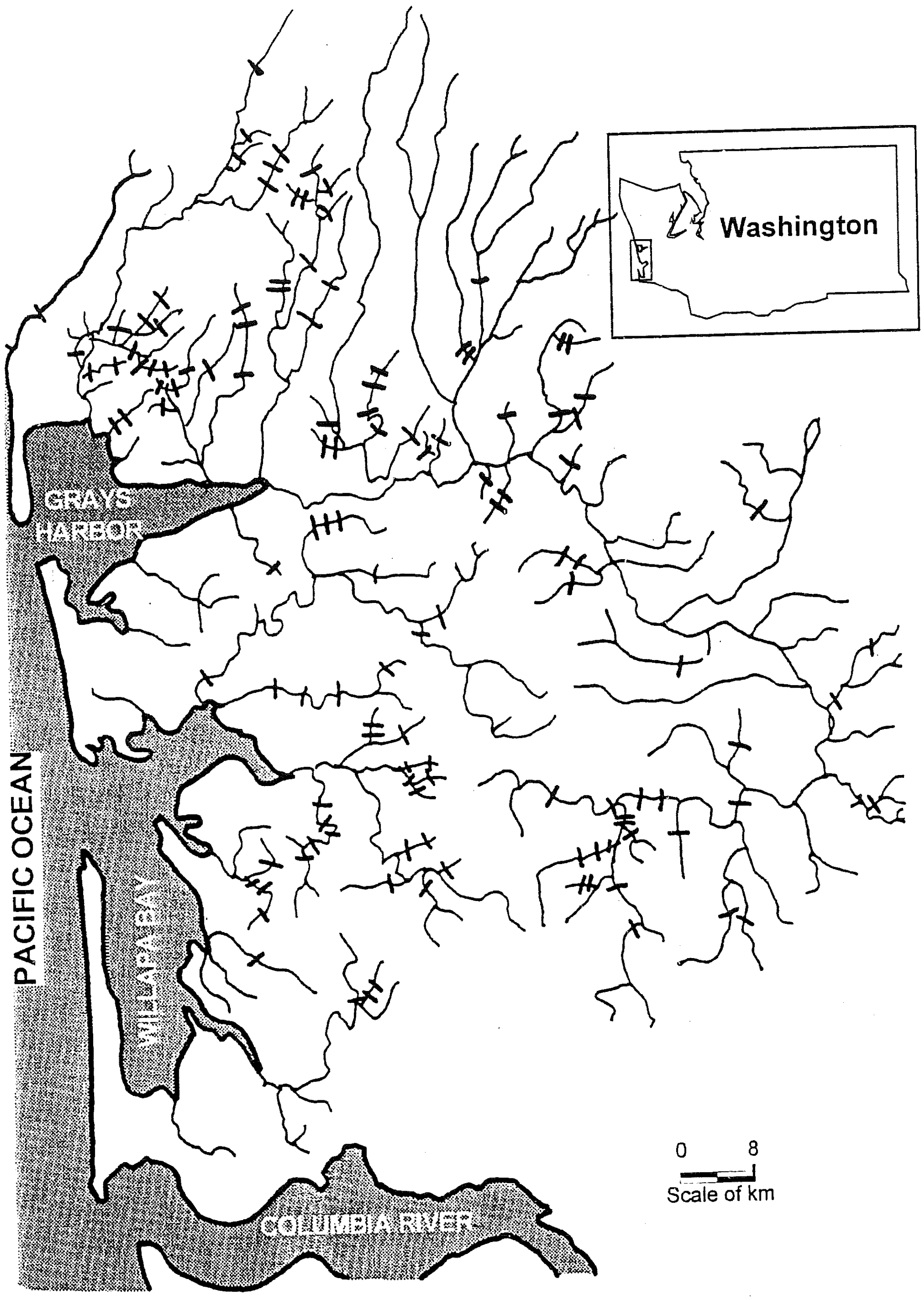


FIGURE 13.9. Locations of splash dams within the Grays Harbor and Willapa Bay drainages in southwestern Washington. Most of these dams operated during the early part of the twentieth century (from Wendler and Deschamps 1955 with permission).

port of logs by splash damming greatly reduced the abundance of LWD in streams where this practice was employed (Sedell and Luchessa 1982).

Until the 1970s, LWD was viewed as an impediment to the upstream migration of anadromous fishes and was deliberately removed to improve passage (Merrell 1951). Stream cleaning was pursued aggressively throughout the Northwest from shortly after World War II until the early 1970s (Narver 1971, Hall and Baker 1982). In many cases, wood which did not prevent upstream access by anadromous fish was removed (Bisson et al. 1987). Even in cases where access was improved, detrimental impacts were associated with this practice, including reduced channel stability and the release of large amounts of stored sediment which damaged fish habitat downstream (Hall and Baker 1982, Bilby 1984).

Removal of trees from riparian areas as a result of logging, agriculture, or development activities decreases LWD by removing the future source of wood input to the channel (Swanson and Lienkaemper 1978, Likens and Bilby 1982). Debris flows, which also remove trees from riparian areas in steep terrain, increase in response to certain land-management activities including road construction and logging (Kauffman 1987, Swanson et al. 1987, Hartman and Scrivener 1990). Reduction in wood input to the channel leads to a gradual decrease in LWD over time as residual material decomposes but is not replaced (Swanson and Lienkaemper 1978, Grette 1985, Bisson et al. 1987, Bilby and Ward 1991). In some cases, especially when removal of riparian trees is followed by commercial salvage of wood from the stream or removal of LWD to accelerate water flow, the rate of decrease in LWD after removal of riparian vegetation can be very rapid (Bilby and Ward 1991).

Logging also alters the characteristics and distribution of LWD. Ralph et al. (1994) reported a decrease in the average diameter of LWD pieces in watersheds subjected to moderate or intensive levels of logging activity. More than 60% of the LWD pieces in stream reaches flowing through old-growth forest were over 50 cm in diameter but only 40 to 45% were this large in reaches in watersheds managed for wood production. In addition, a much larger proportion of the LWD in the logged basins was located along channel margins above the level of water during summer (Figure 13.10). These changes in LWD size and distribution caused a reduction in pool frequency and depth as well as a corresponding increase in fast-water habitats.

Regulations regarding the treatment of stream channels and riparian areas during forest management activities are in place throughout most of the Pacific coastal ecoregion (Chapter 22). The most recent revisions have incorporated considerations for retaining LWD in streams and providing a future supply from the riparian area. Approaches which are currently being applied to address concerns for LWD include establishing buffer strips along the stream in which no harvest is permitted (e.g., Alaska) or that require leaving a specific number of trees per length of channel along the stream (e.g., Washington), or specify a minimum basal area of trees that must be retained along the stream (e.g., Oregon). The efficacy of these various approaches has yet to be determined. Few regulations governing agricultural practices or development in streamside areas address LWD.

The combined effect of various land-use practices over the last century has changed the species composition and age structure of riparian forests in much of the Pacific coastal ecoregion (Booth 1991, Carlson 1991, Franklin 1992). In undisturbed Pacific Northwest watersheds, patches of riparian vegetation, in various stages of recovery from disturbance, form a linear, mosaic pattern (Naiman et al. 1992). The complex assemblage of riparian vegetation types is dictated by upslope erosional processes, the frequency of disturbance, and the topographic and edaphic characteristics of the site. The amount, size, and species of LWD in channels reflects the condition of the adjacent riparian area (Rot 1995). It has been estimated that 60 to 70% of Pacific Northwest forests were in late successional condition (>200 years old) prior to extensive timber harvest in the region (Franklin and Spies 1984, Booth 1991). In contrast, recent surveys of the riparian vegetation on commercial forest land in western Washington indicate that the majority of riparian areas are in an early successional condition (<60 years) many with an overstory of hardwoods—primarily the pioneer species red alder (Carlson 1991).

Reestablishment of the diverse vegetation reflective of the interaction between riparian areas and natural disturbance processes is required in order to reverse the trend of decreasing LWD in Pacific coastal watersheds. A key

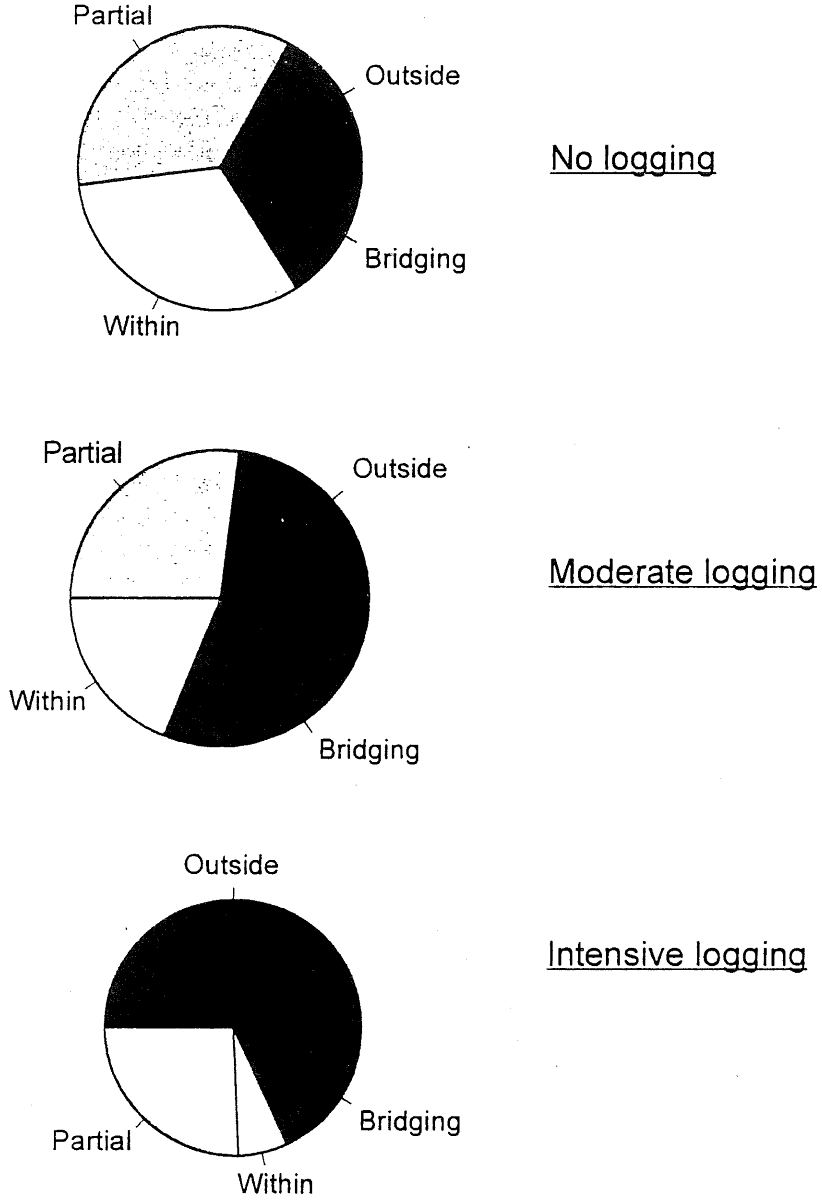


FIGURE 13.10. Distribution of LWD in the stream channels of watersheds subjected to varying levels of logging intensity. *Outside* indicates wood located outside of the low-flow wetted channel, *partial* indicates pieces with a portion of their length in the water, *within* indicates pieces completely in the wetted channel, and *bridging* indicates pieces suspended over the low-flow channel (modified from Ralph et al. 1994).

challenge to achieving this objective is developing a management approach that recognizes and encompasses all the processes responsible for the delivery of LWD to stream channels. The approach also must address management-related alterations in the type, frequency, and severity of disturbances that impact riparian and aquatic systems. Results from such a management approach may take decades to centuries before substantial increases in LWD in streams are achieved. Therefore, successful management approaches will include an adaptive monitoring process which will enable periodic assessment of progress against objectives and allow for corresponding revisions to management plans.

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