SPATIAL AND TEMPORAL DYNAMICS OF WOOD IN HEADWATER STREAMS OF THE PACIFIC NORTHWEST[1]

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ABSTRACT: This paper synthesizes information on the spatial and temporal dynamics of wood in small streams in the Pacific Northwest region of North America. The literature on this topic is somewhat confused due to a lack of an accepted definition of what constitutes "small" streams and what is the relative size of woody debris contained within the channel. This paper presents a matrix that defines woody debris relative to channel size and then discusses the components of a wood budget. Headwater streams are in close proximity to wood sources and, in steeplands, are often tightly constrained by steep hillslopes. Special consideration is given to ecosystem characteristics and to management practices that affect the wood dynamics in this context. Knowledge gaps and uncertainties that can be used to guide future research are identified. Very little is currently known about the role of mass wasting in wood recruitment and storage relative to other processes, such as bank erosion and mortality, in larger streams. Further, very little work has addressed the relative importance of different wood depletion processes, especially those associated with wood transport. The effect of other ecosystem variables on wood dynamics locally across a watershed (from valley bottom to mountaintop) and regionally across the landscape (from maritime to continental climates) is not addressed. Finally, the scientific community has only begun to deal with the effects of management practices on wood quantity, structure, and movement in small streams.
(KEY TERMS: headwater streams; fluvial processes; wood debris; wood budget; channel stability; temporal and spatial variability.)

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INTRODUCTION

This paper presents a review of the dynamics of wood relevant to riparian management around small, steep stream channels, drawing primarily from research conducted in the Pacific Northwest (PNW) region of North America. The focus is small streams because they have received much less scientific attention, and they are subject to different geomorphic driving factors than larger streams and rivers. Further, forest management activity has the potential to alter all aspects of wood availability and delivery to these streams. Because of the branching nature of drainage networks, there are many small streams; forestry may thereby cumulatively be creating major ecological problems in the landscape.

In general, wood within the channel boundary significantly alters flow hydraulics, regulates sediment transport and storage, and influences channel morphology and diversity of channel habitat (e.g., Swanson and Lienkaemper, 1978; Hogan, 1986; Bisson *et al.,* 1987; Montgomery *et al.,* 1995, 1996). In-channel wood plays an important role in determining aquatic habitat conditions and riparian ecology (e.g., Bisson *et al.,* 1987; Bilby and Bisson, 1998). Wood is introduced to the stream channel through a variety of processes including mass wasting, tree fall (blowdown), and bank erosion. Fluvial and nonfluvial processes transport and redistribute wood introduced in upstream areas to downstream locations (e.g., Keller

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and Swanson, 1979; Lienkaemper and Swanson, 1987; Nakamura and Swanson, 1993; Hogan *et al.,* 1998; Johnson *et al.,* 2000a; Benda *et al.,* 2002, 2003; Lancaster *et al.,* 2003). However, wood exerts its greatest geomorphic influence in channels with physical dimensions similar to or smaller than the size of wood (e.g., Bilby and Ward, 1989; Bilby and Bisson, 1998); therefore, wood plays a disproportionately large role in small headwater streams.

Although wood dynamics and channel morphology of streams in the PNW have been studied in some detail, most of the research has occurred in relatively large streams and rivers (> third-order streams on 1:50,000-scale maps). Such results may not be applicable in headwater streams where episodic sediment and wood supply from adjacent hillslopes dominate channel dynamics and where fluvial transport of wood is restricted due to insufficient streamflow and narrow channels. The practical need to understand the physical and ecological roles of small streams has recently been highlighted by interest in restoring downstream ecosystems and the assessment of land management practices in relatively small watersheds (Moore and Richardson, 2003).

Interest in wood dynamics in headwater channels stems from the recognition that these channels represent a distinct class of stream, with characteristic morphologies, processes, and dynamics (see Benda *et al.,* 2005; Hassan *et al.,* 2005). The focus is on the steeper portion of the channel network where episodic wood inputs and sediment from adjacent hillslopes exert significant control on channel dynamics and morphology. In these channels wood tends to accumulate, and sediment is stored upstream of accumulations, transforming steep bedrock channels into alluvial reaches (Massong and Montgomery, 2000; May and Gresswell, 2003b; Montgomery *et al.,* 2003b). In these streams, wood controls channel morphology by regulating the temporal, spatial character and the quantity of sediment stored within the channel zone, and this influences channel stability (e.g., Swanson *et al.,* 1982; Bilby and Ward, 1989).

The paper begins by defining small streams and addressing wood scaling issues relative to channel size. Then the paper reviews the current knowledge regarding each component of the wood budget in small streams. Next the paper discusses the spatial and temporal variability of wood in small streams, with special attention to geographic variability. Then an assessment of available models for the predicting wood dynamics in small streams is provided. The effect on wood dynamics of timber harvesting and riparian management on wood dynamics is considered. Finally, gaps in the knowledge are identified for future research on the wood dynamics in small streams. Due to the limited available information on small forested streams, certain information obtained from larger mountain rivers will be included in this review, and its applicability to small streams is assessed.

DEFINITIONS

The terms "large" and "small" are commonly used in the absolute sense in geomorphology. For instance, in the literature, large woody debris (LWD) is often defined as pieces of wood that are a minimum 3 m in length (e.g., Toews and Moore, 1982) and at least 0.1 m in diameter. Assuming a cylindrical shape, this yields a threshold volume of 0.024 m^3. Others use the same diameter but either 1 m or 2 m (0.008 to 0.016 m^3) length. At a length of 1 m and a diameter of 0.2 m, the volume is 0.03 m^3, so at 1 m length any piece of wood over 0.2 m diameter is considered large (based on volume) by the most common interpretations. For example, Jackson and Sturm (2002) classified wood as large when the pieces had a diameter of 0.1 m and a length of 0.5 m in small streams (for more classifications see Table 1). It is well accepted that LWD can have an important influence on channel morphology and aquatic habitats, but the nature of that influence depends on the size of pieces relative to that of the channel.

A stream is commonly considered "small" if its channel is less than some arbitrary width, often ranging between 1 and 3 m, although this may vary greatly. Usually there is no requirement regarding other channel dimensions (e.g., depth) or properties (e.g., substrate, gradient). A problem with specifying absolute terms (e.g., width) is that there is a diverse range of channel morphologies that are independent of size. For instance, a 1 m wide channel can have, at one end of the morphological spectrum, a stable step pool morphology, where instream boulders are of a size comparable to that of the channel, or, at the other end, a sand-bed channel that has bed forms composed of the aggregate of many small particles that change on all rising and falling flows. Each channel type is influenced in different ways by LWD. Church (1992) proposed that a small stream is one that has bed material that is large relative to channel depth, and this has been used in certain channel classification schemes (e.g., British Columbia Ministry of Forests, 1996a, b). Use of such relative definitions emphasizes the possible functional roles and mobility of the defining elements.

The lack of common terms has made review of LWD in small streams difficult because the relative sizes of the wood and channel cannot be determined. For this review debris has been classified relative to

TABLE 1. Definition of Large Wood in Various Studies.

Minimum Diameter (m)	Minimum Length (m)	Channel Width (m)	Location	References
0.10	1.5	5.5-10.9	Coweeta, North Carolina	Hedman *et al.* (1996)
0.10	0.5	0.6-3.7	Southeast Alaska	Gomi *et al.* (2001)
0.15	2.0	6.4-7.0	Yellowstone National Park, Wyoming	Young (1994)
0.10	1.0	3.7-10.2	Central Colorado	Richmond and Fausch (1995)
0.15	3.0	5.3-22.9*	Western Oregon	Wing and Skaugset (2002)
0.10	1.0	3.9-36.7	Northwest Montana	Hauer *et al.* (1999)
0.10	1.0	8.2-31.4	Southwest Alaska	Murphy and Koski (1989)
0.20	2.0	3.3-4.8	Costal Oregon	May and Gresswell (2003b)
0.10	3.0	–	Western Washington	Ralph *et al.* (1994)
0.10	0.5	< 4	Coastal Washington	Jackson and Sturm (2002)
0.10	1.0	2.4-5.4	Costal British Columbia	Fausch and Northcote(1992)
0.08	1.8	2.9-14	Northern California	Benda *et al.* (2002)
0.10	3.0	5-15	Carnation Creek, British Columbia	Toews and Moore (1982)
0.10	–	5-20	Queen Charlottes, British Columbia	Hogan (1987)
0.10	1.0	9.0-23.0	Western Cascade, Oregon	Nakamura and Swanson(1994)
0.20	1.5	5.1-25.9	Southwest Alaska	Robison and Beschta (1990b)
0.10	2.0	3.1-23.5	Southwestern Washington	Bilby and Ward (1991)
0.20	1.0	4.8-12.3	Cascade Mountain, Washington	Rot *et al.* (2000)
0.10	1.0	–	Western Cascade, Oregon	Faustini and Jones (2003)
0.10	1.0	0.6-3.2	Yellowstone National Park, Wyoming	Marcus *et al.* (2002)

*Mean values for each stream order.

TABLE 2. Definition Matrix of Relative Wood Debris Size and Relative Channel Size.

	Relative LWD Size Ll/Wb			Relative Channel Size Ll/Wb		
Ld/Db	**< 0.3**	**0.3-1.0**	**> 1.0**	**< 0.3**	**0.3-1.0**	**> 1.0**
<0.3	S	M	L	Large	Intermediate	Small
0.3-1.0	M	L	L	Intermediate	Small	Small
> 1.0	L	L	VL	Small	Small	Very Small

Notes: Ll = log length; Ld = log diameter; Wb = channel bankfull width; Db = channel bankfull depth; S = small woody debris (SWD); M = intermediate wood debris (MWD); L = large woody debris (LWD); VL = very large organic debris; D = dominant grain size (~ D_{95}). D/Ld should be meaningful such that D/Ld: > 1 debris less important because bed material provides primary structural functionality; 0.3-1.0 debris more important and structurally functional; < 0.3 debris critically important.

the channel according to the matrix presented in Table 2. In this manner, size is implicitly considered and arbitrary absolute terms are avoided. Nevertheless, the matrix thresholds remain arbitrary until further analysis is completed to justify their use. This approach allows the use of data from channels that are heavily laden with LWD regardless of their absolute width; that is, if the channel has a riffle pool morphology and LWD (by the above matrix definition) is present, then reviews of larger channels are relevant, in that they have the same dimensional characteristics. Therefore, review of large streams (in absolute terms) is relevant in this context.

WOOD BUDGET

An instream wood budget accounts for where wood comes from, where it is delivered to, where it is stored, and how it is transported or depleted from a given drainage basin or a single stream reach. Single or multiple wood budgets can be combined to construct a budget for an entire watershed as illustrated in Figure 1. In headwater streams wood is delivered to channels directly from upland forests on steep slopes coupled to the channel or from the foot of hillslope and near-stream riparian zones. A comprehensive review of the concept and the formulation of a wood budget is provided by Benda *et al.* (2003). For examples of applications of the wood budget approach see Martin and Benda (2001), Benda *et al.* (2002), and Benda and Sias (2003). Here the fundamental components of a wood budget are briefly discussed, while Table 3 provides a summary of some published wood budgets. From a forest management context there is potential to affect each component of the budget, so it is important to know the relative importance of each component and which are most susceptible to impact.

Wood Recruitment

In mountainous headwater streams, recruitment of wood from mass movement processes is highly variable in both space and time. Mass wasting events may deliver wood directly to stream channels because there is a minimal low gradient terrain to intercept wood (Nakamura and Swanson, 2003). Depending on the geological and geomorphological setting, the temporal frequency of spatially extensive mass wasting events can range from a few decades to more than 10,000 years (Reneau and Dietrich, 1990, 1991; Schwab, 1998, Nakamura and Swanson, 2003; May and Gresswell, 2004). The potential of landslides in mountainous landscapes can be increased by logging, road building, wind throw wildfire, earthquakes, and volcanic activity (Harmon *et al.,* 1986; Lienkaemper and Swanson, 1987; Nakamura and Swanson, 2003).

Research in the PNW has shown that landslides can provide a substantial quantity of wood to headwater streams (Keller and Swanson, 1979; Schwab, 1998; Hogan *et al.,* 1998; May, 2002; May and Gresswell, 2003a; Reeves *et al.,* 2003). In contrast, other studies in Alaska, California, and Washington have found that mass movements may be of limited importance in supplying wood to larger streams (Murphy and Koski, 1989; Johnson *et al.,* 2000a; Martin and Benda, 2001; Benda *et al.,* 2002; Gomi *et al.,* 2004; May and Gresswell, 2004). Another wood source into small streams is snow avalanches, a process that commonly destroys forest stands in the runout pathway. Repeated avalanches down established pathways prevent the growth of mature forests, so this process may be associated with the recruitment of relatively small wood. Where snow avalanches are an important landscape process, they provide the greatest wood recruitment in areas where the channel and hillslopes are coupled (Dave McClung, The University of British Columbia, January 6, 2005, personal communication) (see Figure 1).

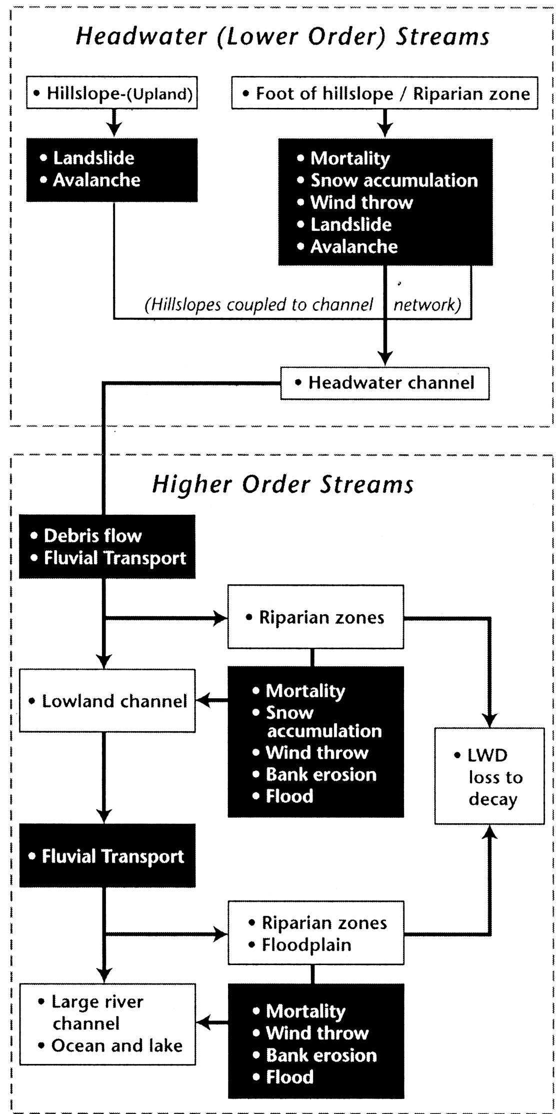

Figure 1. Flow Diagram for a Wood Budget in a Watershed. Open squares represent geomorphic areas related to locations for the sources and storages of wood, and filled squares represent processes that affect wood transport.

Severe windstorms snap tree stems and branches and in many cases uproot entire trees or stands of trees. Wind throw along both large and small streams is an important wood recruitment process (e.g., Harmon *et. al.,* 1986; Lienkaemper and Swanson, 1987; Nakamura and Swanson, 1993, May and Gresswell, 2003a) that may be influenced by topographic position

TABLE 3. Dynamics of Wood in Channels: Input, Storage, and Output.*

Creek/River	Location	Channel Width (m)	Landuse	INPUT: Mortality (m^3/km/yr)	INPUT: Percent of Wood Volume	INPUT: Windthrow (m^3/km/yr)	INPUT: Percent of Wood Volume	INPUT: Bank Erosion (m^3/km/yr)
Little Lost Man, Prairie	California	6.4-19.8	Old Growth	–	–	–	–	–
H.J. Andrews**	Oregon	3.5-24	Logged	–	–	–	69[f]	–
	Alaska	8.2-31.4	Old Growth	–	20-33	–	20-48	–
Little Lost Man, Prairie	California	0.2-43	Managed	1.1-30.6 (4.0)[c]	–	–	–	0-7.2 (3.2)[c]
Van Duzen	Alaska	7.4-24	Old Growth	0 to 7.4 (2.5)[c]	–	–	–	1.0 to 5.8 (3.3)[c]
Game Creek**	Alaska	3.3-23.8	Old Growth	0.1 to 8.1	–	–	–	1-16
	Alaska	4.6-8.8	Old Growth	–	–	–	–	–
		12.8-25.9	Old Growth	–	–	–	–	–
Queets River	Washington	51-398	Old Growth	–	–	–	–	–
Olympic Peninsula	Washington	7.1-16.6	Logged/Second Growth	–	–	–	–	–
Queen Charlotte Islands	British Columbia	9.4-31.7	Unlogged	–	–	–	–	–
		10.3-35.7	Logged	–	–	–	–	–
Cherry Creek	Oregon	3.3-4.8	Old Growth/Logged	–	5	–	34-61	–
Cummins Creek	Oregon	–	Old Growth/Logged	–	54[g]	–	–	–
Deschutes River	Washington	–	–	–	–	–	–	–

TABLE 3. (cont'd.)

Creek/River	STORAGE: Storage: Volume (m^3/km)	STORAGE: Residence Time (mean) (yr)	STORAGE: Residence Time (max) (yr)	STORAGE: Change in Storage (m^3/km/yr)	OUTPUT: Transported (percent)	OUTPUT: Depletion[a] (percent/yr)	OUTPUT: Decay[b] (percent/yr)	References
Little Lost Man, Prairie	290-1,850	100	>200	–		–	–	Keller and Swanson (1979)
H.J. Andrews**	175-780	12-83	–	–	6-65[d]	–	–	Lienkaemper and Swanson (1987)
	–	54	226	–		1-3	–	Murphy and Koski (1989)
Little Lost Man, Prairie	10-3,140	–	–	–	–	0[e]	0[e]	Benda *et al.* (2002)
Van Duzen	500-4,000	–	–	–	–	0[e]	0[e]	
Game Creek**	102-767	–	–	–	–	0[e]	0[e]	Martin and Benda (2001)
	360-600	–	–	–	–	–	–	Robison and Beschta (1990a)
	570-1,000	–	–	–	–	–	–	
Queets River	320-10,000	30	1,400	–	–	3	–	Hyatt and Naiman (2001)
Olympic Peninsula	100-1,000	–	–	(-2)-(-39)	-	1.7 (sd=4.4)	–	McHenry *et al.* (1998)
Queen Charlotte Islands	382-4,593 (1,908)	–	–	–	–	–	–	Hogan *et al.* (1998)
	182-3713 (1,122)	–	–	–	–	–	–	
Cherry Creek	–	–	–	–	1	–	–	May and Gresswell (2003a)
Cummins Creek	1,520	–	–	–	–	–	–	Reeves *et al.* (2003)
Deschutes River	–	–	–	–	–	–	2.6-3.8	Bilby *et al.* (1999)

*Total input of wood includes all processes related to recruitment of wood.
**Data are for several creeks.
[a]Depletion includes all mechanisms for wood loss (including transport, abrasion, and decay).
[b]Primarily biogenic decay.
[c]Average values in brackets.
[d]Percent transported over 10 years on average.
[e]Assumed value.
[f]Recruited volume from riparian areas.
[g]Recruitment from all riparian sources.

within a watershed. Since small headwater streams are high in the channel network, often near a ridge top, wood recruitment by wind throw may be greater in them compared to their lowland counterparts (May and Gresswell, 2003a; Nakamura and Swanson, 2003). However, local edges of terrain features, relative to prevailing wind direction, could also prove highly influential.

Fires, insect infestations, and disease outbreaks are other processes that influence the recruitment of wood to streams. If high severity fires burn extensive areas around headwater streams, the amounts and characteristics of wood input to streams may be altered for long periods; wood inputs are likely to increase immediately after fires (Nakamura and Swanson, 2003). Burned wood may also break into smaller pieces that can choke the channel, thereby increasing channel instability and downstream fluvial transport of wood (e.g., Berg *et al.,* 2002). The degree of fire damage to stands depends on fire severity, type (ground, surface, or crown), and spatial extent (Agee, 1993). Patterns of mortality due to forest fire vary among regional fire regimes, season, and topography. Compared to floodplains, upland areas, including small streams and riparian zones, are more frequently affected by forest fires because of their relatively dry conditions and strong winds (Agee, 1993). Fire can also affect the wood budget by altering the age structure of the forest, initiating episodic pulses of wood recruitment, consuming existing dead wood, and influencing the mobility of instream wood (Young, 1994; Tinker and Knight, 2000; Zelt and Wohl, 2004). Finally, insect infestations and disease outbreaks can episodically affect stand mortality in large areas. In the PNW, many disease and insect outbreaks appear to be related to fire suppression or exotic pathogens (Hessburg *et al.,* 1994; Swetnam *et al.,* 1995; Dwire and Kauffman, 2003). However, most insects and diseases affect only a single tree species, so the net effect on wood recruitment will depend upon the composition of the stand (Harmon *et al.,* 1986).

Streambank erosion may not significantly contribute wood to steep headwater streams because the channel is constrained by the adjacent hillslopes (Nakamura and Swanson, 2003) and banks are often semi- or non-alluvial (e.g., Halwas and Church, 2002). Actual rates of bank erosion in headwater constrained streams are poorly documented but are believed to be minimal. However, in gentler areas with less bedrock constraints, bank erosion is likely (expected) to be a significant source of wood into channels. In headwater streams, wood is often suspended above the channel banks due to relatively narrow channel widths (relative to tree heights and diameters) and hillslope confinement. Direct input to the channel may not occur until a log is either broken or fragmented (Nakamura and Swanson, 1993).

Wood Storage

Once delivered to the stream system, wood is stored for various durations in several different environments; these include areas in riparian zones and associated floodplains and within the channel boundaries (Figure 1, Table 3). While the amount of wood stored can be quantified at a given point in time, it is difficult to quantify long term changes in the volume of wood. This is particularly true in small streams where it is not feasible to use historical aerial photographs due to resolution limitations and views obscured by overhanging vegetation. A common practice when attempting to construct wood budgets is to estimate recruitment rates based on the volume of wood stored over some period of time (Martin and Benda, 2001; Benda *et al.,* 2002); however, this approach usually underestimates the gross recruitment rate because it ignores the exchange of fluvially transported wood with neighboring stream reaches. Further, recruitment rates estimated from storage volumes are often underestimated because it is assumed that wood decay is negligible, which is rarely the case (e.g., Harmon *et al.,* 1986). However, recent studies showed that buried wood in streams can last decades to centuries (e.g., Guyette *et al.,* 2002).

Difficulties in assessing wood storage in small streams can arise from unclear definitions of what constitutes stored wood in the stream. In particular, few studies have referenced the criterion used to determine that portion of the wood actually interacting with the stream and fluvial processes. Robison and Beschta (1990a) examined the storage of wood in distinct zones within the stream system and developed a classification system in which they identified and distinguished between wood within the channel and wood on the banks. Storage of wood within a system can be likened to a wood reservoir that has a characteristic residence time (Keller and Tally, 1979; Hogan, 1989). Wood reservoirs can be used to study wood dynamics over a range of temporal and spatial scales. In headwater streams, the temporal scale is likely to be a function of the frequency and magnitude of the wood mobilizing events (see the following section).

Wood Output

Wood stored in the fluvial system is transferred out of a reach by downstream transport or lost through abrasion or *in-situ* decomposition. Log stability in channels is controlled by many factors, including piece dimensions (length and diameter) relative to the channel, wood integrity, attached root wads, and degree of anchoring in the channel bed and bank (e.g., Montgomery *et al.,* 2003a,b). Braudrick *et al.* (1997) suggested three mechanisms of wood transport: floating in a congested manner (high concentration) by streamflow, floating in an uncongested manner, and debris flows (for more details see the section on modeling). Field studies show that log movement is more likely to occur as channel size increases and when logs are shorter than bankfull width, implying that fluvial transport of wood is more significant in higher-order streams (e.g., Bilby and Bisson, 1998). McHenry *et al.* (1998) examined changes in the composition of old-growth and second-growth wood pieces in order to assess changes to storage in 28 small streams. They found that the balance of new inputs from second growth was not sufficient to offset the loss of old-growth pieces in the channel, and the total wood storage was decreasing (Table 2). Because headwater streams commonly contain wood sizes much longer than channel width, fluvial transport of wood by streamflow is limited to extreme floods; Millard (2001) found that wood did not move along any streams with widths less than 1 m, regardless of the gradient. This can lead to large accumulations of wood in these streams (e.g., Jackson and Sturm, 2002; Lancaster *et al.,* 2003; May and Gresswell, 2003b). In steep terrain, debris flows are an effective evacuating agent of accumulated wood; debris flows transport wood downstream to larger channels (Benda *et al.,* 2005).

Wood is lost from the fluvial system through mechanical attrition (including decomposition, abrasion, and fragmentation); these have been summarized in detail by Harmon *et al.* (1986) and Webster and Benfield (1986). Temperature and oxygen have been identified as the main environmental controls of decay in both aquatic and terrestrial environments (Sedell *et al.,* 1988), while differences between hardwood and softwood species are less pronounced (Bilby *et al.,* 1999). In high elevation small streams, cooler air and water temperatures may limit microbial activity and the decay of wood.

Few studies have investigated the effects of relative wood submergence on decay processes (e.g., Bilby *et al.,* 1999). Continuously submerged or waterlogged wood typically decays slowly because of anaerobic conditions (Keller and Swanson, 1979), while wood submerged only during higher flow is thought to experience faster decomposition and fragmentation (Sedell *et al.,* 1988; Cederholm *et al.,* 1997). Fluctuation in wood moisture conditions and resultant shrinkage and expansion of wood induce cracks that increase access to microbes (Harmon *et al.,* 1986). Consequently, both terrestrial and aquatic wetting patterns need to be considered in order to characterize wood decay in small channels.

TEMPORAL AND SPATIAL VARIABILITY OF WOOD IN SMALL STREAMS

Spatial and Temporal Variability

The variability in wood loading, either at a point in time or in different portions of the channel network, has received considerable attention in watershed management. Bilby and Ward (1989) reported that wood abundance is inversely related to stream size, with the smallest streams having the most wood per unit area. A compilation of data from streams throughout the PNW illustrates that the variation in wood loading increases as stream size decreases (Figure 2a); when scaled by channel width (Figure 2b), values of wood abundance relative to channel size are much higher for small streams. Caution should be taken when interpreting the data in Figure 2 because the minimum size of wood included in the samples was not consistent (wood length criteria ranged from 0.5 to 2m), stream reaches drained a mixture of old-growth and managed forests, and Bilby and Ward (1989) counted only wood that provided a functional role in the channel while all other studies reported the total number of pieces. In Figure 2 a threshold occurs that corresponds to channels approximately 5 m wide, which is similar to the pattern observed by Jackson and Sturm (2002). Note that the relationship in Figure 2 is inverse to that reported in Jackson and Sturm (2002), which reports the product of wood loading and channel width, not the quotient. The negative exponent in the power function relationship (Figure 2b) is not equal to one, which indicates that the decline is not constant. This pattern is likely due to the increased transport capacity of wood (based on channel width and flow depth) as channel size increases.

However, in the PNW, channels less than 5 m wide are typically steep headwater streams prone to debris flows, which could drastically reduce channel wood loads (May and Gresswell, 2003b). During the interval between debris flows, in-channel wood load gradually increases (Bovis *et al.,* 1998; May and Gresswell, 2003b). This has important implications for temporal and spatial variability of wood abundance in small streams, indicating that recruitment processes (and rates) from the adjacent hillslopes determine the

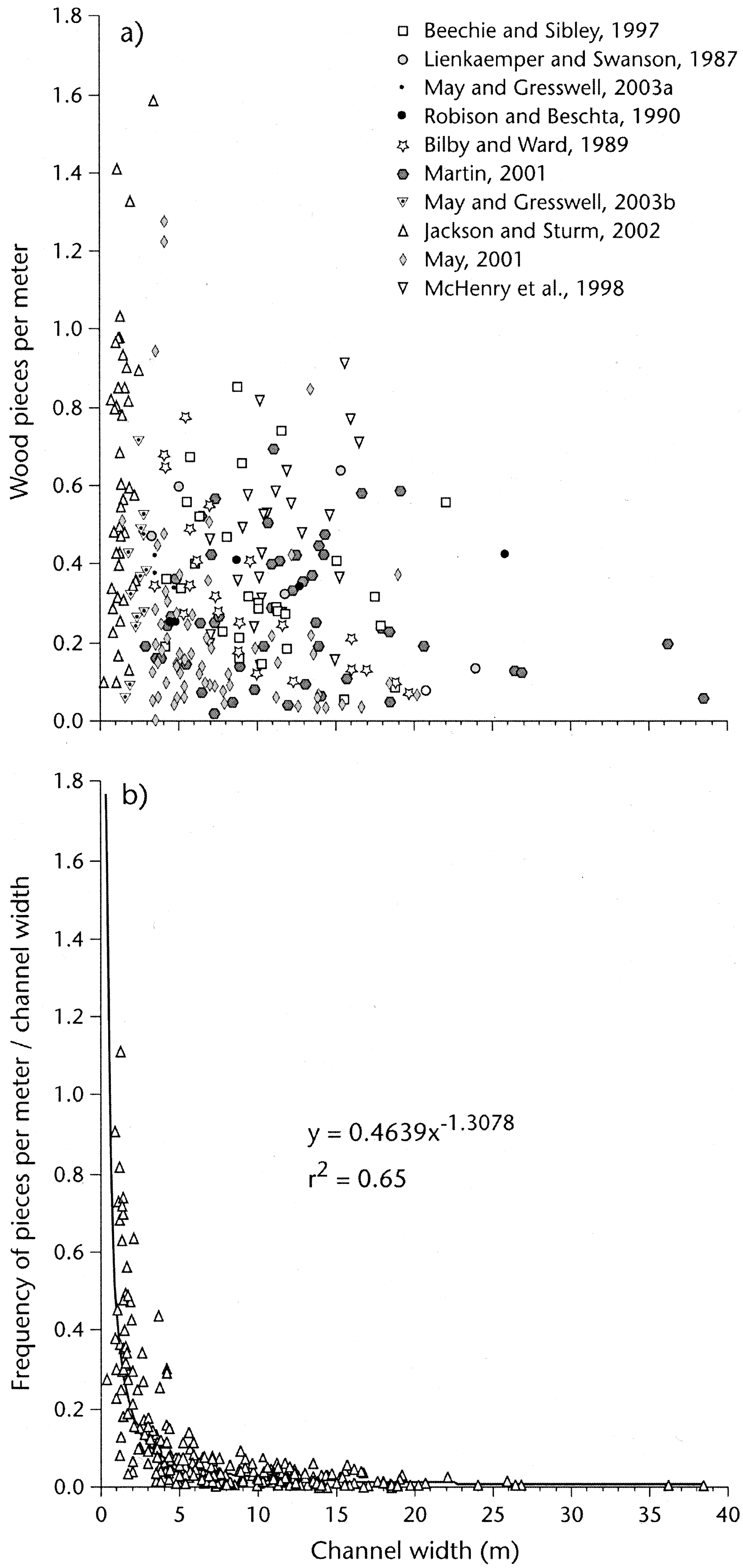

Figure 2. A Compilation of Data on Wood Abundance From 262 Stream Reaches in the Pacific Northwest (modified from Jackson and Sturm, 2002): (a) Large Wood Abundance Per Unit of Channel Length, and (b) Large Wood (numbers per meter of channel length) Scaled by Bankfull Channel Width for the Data Presented in (a).

spatial distribution and abundance of wood, while the time since the last debris flow explains the variance.

During the interval between debris flow events, headwater streams provide a critical link in watershed scale sediment routing. Wood makes these channels highly retentive by physically obstructing sediment transport and forming steps (Keller and Swanson, 1979; Megahan, 1982; Bilby, 1981; Hogan *et al.,* 1998; Gomi *et al.,* 2001, 2003; Lancaster *et al.,* 2003; May and Gresswell, 2003b). Steps formed by wood increase the streambed roughness, dissipate energy, and thereby reduce the potential for sediment transport. Accumulations of wood can function as long-term sediment reservoirs that are periodically evacuated during extreme events. If wood recruitment is reduced, the storage capacity of headwater streams can be diminished, resulting in newly freed sediment being delivered directly to downstream areas (e.g., Benda *et al.,* 2005). Changes to sediment supply rate and pattern may have adverse effects on aquatic organisms adapted to episodic disturbances or chronic sedimentation.

In addition to storing sediment in headwater streams, wood also play a dynamic role in the mass flow itself. Wood represents a sizable fraction of the total debris flow volume (May, 2002; Lancaster *et al.,* 2003), and recent modeling efforts suggest that velocity reduction due to the entrainment of wood in the runout path has the potential to decrease the travel distance of debris flows (Lancaster *et al.,* 2003). Therefore, wood abundance in headwater streams is of primary concern for policy and management because runout length determines the destructive potential of debris flows.

There are two source areas for wood that can be incorporated into the debris flow volume: wood scoured from headwater streams, and trees growing along the runout path that are toppled into the flow. In basins that have undergone intensive timber harvest, the major source of material is "legacy wood," defined as wood that is unrelated in species or size class to the surrounding forest (May, 2002). Because of this legacy and the depletion of other sources, debris flows can become an increasingly important source of wood to main stem rivers. For example, many streamside forests in the Oregon Coast Range no longer contain large trees because old-growth conifers have been replaced by young hardwood stands. In addition, wood was intentionally removed or "cleaned" from streams by past management practices. The combination of reduced storage by past stream cleaning, a loss of recruitment from streamside forests because of a change in species and/or size class of trees, and an increase in landslide frequency associated with timber harvest may result in a net increase in the relative importance of debris flows as a source of wood to larger streams that drain industrial timberlands (May, 2002; Montgomery *et al.,* 2003a). However, the relative importance of wood delivered by debris flows to larger streams remains controversial (Martin and Benda, 2001; May, 2002; Benda and Sias, 2003; Montgomery *et al.,* 2003a,b; Reeves *et al.,* 2003).

The architecture of logjams created by debris flows has many unique characteristics. Wood travels at the front of the mass flow and creates a woody "snout" that is followed by a sediment rich tail. Woody snouts function to trap sediment traveling in the flow and form effective dams that retain sediment for long periods (Hogan *et al.,* 1998; Lancaster *et al.,* 2003; May and Gresswell, 2003b). By forming dams, the episodic signal of sediment delivery from headwater streams is not translated to downstream areas. If these wood dams form in a narrow valley, the upstream sediment reservoir creates aggradation along 101 to 102 meters of channel as a function of overall channel gradient. These obstructions are referred to as "vertical jams" (Hogan and Bird, 1998) because the channel is not free to move laterally around the jam, so sediment builds vertically behind it. Debris flow deposits may be the only mechanism for creating large logjams in intermediate size streams (valley widths 5 to 30 m) where fluvial power is competent to mobilize wood. While the logjams are effectively trapping sediment and not preventing sediment passage, the downstream channel bed frequently degrades. Hogan *et al.,* (1998) documented cases where the degraded zone extended for over 100 bankfull widths in length.

When debris flows enter larger streams and do not form discrete deposits, congested transport of wood occurs (Braudrick *et al.,* 1997). During congested transport of wood, logs move together as a single mass and occupy a large proportion of the channel width (Braudrick *et al.,* 1997). Because wood input rates are higher and channel dimensions are small relative to wood size, congested transport is more likely to occur in small to mid-order streams than in larger rivers (> fourth-order streams) (Braudrick *et al.,* 1997). This congested transport of wood through moderate-size channels can result in the removal of streamside forests and altered channel conditions over distances of kilometers (Johnson *et al.,* 2000b).

Variability Due to Biogeoclimatic Factors

In the northern areas of the PNW, streams in low land portions of a watershed are generally coincident with the coastal western hemlock (CWH) biogeoclimatic zone and occasionally in the coastal Douglas-fir (CDF) biogeoclimatic zones. These forests have relatively high productivity, with a mean annual increment (MAI) of at least 6.4 m^3/ha/yr (Mackinnon *et al.,* 1991). Typical coniferous tree species in these zones include western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), and Douglas-fir (*Psendotsuga marziesii*), with Sitka spruce (*Picea sitchensis*) common along relatively wet valley bottoms and floodplains (Nuszdorfer *et al.,*1991; Pojar *et al.,* 1991a). Stand destroying disturbance in most riparian zones is infrequent. For example, in some coastal CWH watersheds, stand replacement disturbance in riparian zones likely occurs over intervals of 400 to 1,000 years (Clayoquot Sound Scientific Panel, 1995). Wind throw is the most common form of catastrophic disturbance in these areas and can affect single trees, small patches, or, more rarely, complete forest stands (Waring and Franklin, 1979).

Farther upslope in coastal areas, the subalpine forests of the mountain hemlock (MH) biogeoclimatic zone dominate the landscape. In this zone, tree growth generally decreases with increasing elevation due to shorter growing seasons, the increased duration of snow cover, and cooler temperatures (Pojar *et al.,* 1991b). These forests have relatively low productivity, with the MAI ranging from 0.8 to 3.4 m^3/ha/yr (Mackinnon *et al.,* 1991). Lower elevations throughout the zone are heavily forested but grade into parkland (individual trees or clumps of trees among patches of mainly low shrubs) at higher elevations. Typical coniferous tree species throughout the zone include mountain hemlock (*Tsuga mertensiana*), amabilis fir (*Abies amabilis*), and yellow cedar (*Chamaecyparis nootkatensis*) (Pojar *et al.,* 1991b). Forests of the MH are generally resilient and infrequently disturbed (cycles in excess of 200 years). However, forested MH areas are slow to recover once a disturbance has occurred (Klinka and Chourmouzis, 2001).

Several inferences relating to the dynamics of wood can be drawn from these broad biogeoclimatic zones and their distribution within a watershed. First, the MAI describes the average production volume per year for a forest of known age and has important consequences for recruitment rates of wood to the channel. In a watershed with similar aged forests throughout, small subalpine channels will tend to have less wood (in volume) available for recruitment than larger lowland streams. However, this reduction in the potential wood supply may be augmented by differences in both episodic and chronic supply rates. For example, the rate of chronic mortality (as indexed by maximum tree age of common species) ranges from 500 to 1,000 years in the CWH and from 590 to 800 years in the MH zone (Burns and Honkala, 1990). The number of individual stems delivered to the channel through chronic wind throw and mortality are likely greater in small streams as they pass through subalpine forests of MH zone because trees generally live longer in the CWH. Inputs of wood from subalpine forests such as the MH may also reinforce the randomness observed in storage volumes, as the forests are often discontinuous (i.e., alternating between forest and parkland).

Second, the size distribution of logs delivered to a small, upland channel is expected to differ from those delivered to a larger, lowland channel, and this may affect wood stability and transport processes. For example, mature trees growing along a small upland channel in the MH may range from 0.6 to 1.5 m in diameter (measured at breast height), while those growing along a large lowland channel in the CWH or CDF may range from 1 to 6 m (Burns and Honkala, 1990). Given that the buoyant force acting on a log is a function of log diameter for logs partially submerged by the flow (Braudrick and Grant, 2000), critical water depths required to float a log in the MH zone may be 30 to 60 percent of those in larger streams in the CWH and CDF zones (ignoring differences in wood density among zones).

Third, differences in local climate influence decay characteristics of wood stored in a channel. In the CWH and CDF zones, mean annual air temperature ranges from about 5 to 11°C, and mean annual precipitation ranges from about 650 to at least 4,400 mm, with anywhere from 5 to 50 percent falling as snow (Nuszdorfer *et al.,* 1991; Pojar *et al.,* 1991a). In the higher elevations associated with the MH zone, mean annual air temperature ranges from 0 to 5°C, and mean annual precipitation ranges from 1,700 to 5,000 mm, with 20 to 70 percent of this falling as snow (Brooke *et al.,* 1970; Pojar *et al.,* 1991b). Lower precipitation as rain and cooler temperatures in the MH zone reduce microbial activity, while smaller log diameters allow a greater proportion of a log to remain submerged (hence limiting the oxygen available to microbes) as channel depth decreases with decreasing channel size. In contrast, increases in light associated with some MH zone forests (especially in parkland ecosystems) may increase microbial activity.

Changing ecosystem characteristics are a confounding influence on the study of wood processes, including comparisons of wood input, storage, transport, and decay, and underscore the importance of considering ecosystem characteristics or classification such as biogeoclimatic zonation to understand the dynamics of wood. Examples in CWH, CDF, and MH zones have been considered in this section. Full ranges of biogeoclimatic zones should be included for evaluating wood dynamics in small streams in the PNW.

MODELING WOOD DYNAMICS

Models

Physical, theoretical, and computer simulated models have been developed in order to estimate woody debris dynamics at various spatial and temporal scales. Gregory *et al.* (2003) provide the most recent and comprehensive review of available models. They compared 14 models (see Gregory *et al.,* 2003,Tables 1A and 1B); 11 were developed in the PNW, 2 in the U.S. Midwest, and 1 in the Rocky Mountain region. Table 4 is a modified and updated version of Tables 1A and 1B compiled by Gregory *et al.* (2003). The comparison in Table 4 is limited to variables related to wood input and output. Most of the existing models are deterministic, while three are stochastic based on probabilities of wood processes and rates. In order to complement Gregory *et al.* (2003), this review is focused on a general summary of their models and additionally includes the Lancaster *et al.* (2003) model. Limitations of the wood budget framework for modeling wood in small streams are discussed.

Channel network structure is important when modeling the downstream transfer of wood and sediment. Lancaster *et al.* (2003) examined the episodic and chronic transfer of wood and sediment from headwater areas to downstream systems in a small watershed in the Oregon Coast Range. They adopted a triangulated, irregular network for terrain representation and operated stochastic precipitation and runoff generation models based on algorithms of drainage area calculations. For headwater streams, the model predicted that a large amount of wood and sediment was stored within channels and their valleys, materials that are released following the disintegration and decay of woody debris dams.

A range of wood recruitment processes has been incorporated into the models in Table 4. Some of these models specifically incorporate within-channel wood transport, while others assume a depletion rate. A number of models expressly predict wood decay, yet others did not include decomposition rates at all. The time frame of these models ranges from 100 years to over 1,000 years, while model time steps ranged from single years to decades (Table 4). From the empirical evidence it appears that tree mortality, fire, insect or disease outbreaks, mass wasting, and bank erosion are the main processes of wood recruitment in headwater streams. All models except Downs and Simon (2001) consider tree mortality as the primary mechanism for wood input. Two models (Benda and Dunne, 1997a,b; Lancaster *et al.,* 2003) incorporate four processes (tree mortality, fire, bank erosion, and mass wasting) to predict wood input to streams. The capabilities of the stochastic models of Benda and Dunne (1997a,b) and Lancaster *et al.* (2003) are believed to provide the most flexible framework for use in headwater streams and thus will be emphasized herein.

Flume experiments have been conducted to investigate the mobility of wood, the effect of wood orientation on pool scour depth, and the impact of wood on channel morphology (e.g., Braudrick *et al.,* 1997; Braudrick and Grant, 2001; Wallerstein *et al.,* 2001). Braudrick and Grant (2001) tested a semiquantitative model for wood transport by fluvial processes. Flume experiments were conducted to examine the interactions between channel geometry and hydraulics and the travel distance and deposition of floating wood. The model is based upon wood piece and channel characteristics averaged over a reach. In the model, the probability of wood being deposited in the channel depends on three dimensionless ratios: piece length to mean channel width, piece length to mean radius of curvature, and buoyant depth to average channel depth. Travel distance increased as the former two variables decreased and was unrelated to the latter variable. Instead, the proportion of channel where the flow depth exceeded the buoyant depth restricted travel distance.

Braudrick *et al.* (1997) introduced an analytical model that predicts flow conditions needed to entrain individual wood pieces and then conducted flume experiments to examine wood movement as a function of flow conditions, channel morphology, and wood size input rates. They reported three distinct transport regimes: (1) uncongested, in which individual pieces moved without interaction between them, occupying less than 10 percent of the channel area; (2) congested, in which logs move in groups, occupying more than 33 percent of the channel area; and (3) semicongested, which is an intermediate state between the first two regimes. Given a relatively high input of wood to headwater streams and the relatively small channel size to piece size relation, Braudrick *et al.* (1997) predicted that the congested regime dominates wood transport through small channels.

Wood Budgeting

Another approach to predicting riparian wood dynamics is through the construction of wood budgets; these are based on a flexible conceptual framework similar to the long standing approach of sediment budgeting (Dietrich and Dunne, 1978; Dietrich *et al.,* 1982; Reid and Dunne, 1996, 2003; Slaymaker, 2003) and have been described by Benda and Sias (2003). However, the application of this

TABLE 4. Comparison of Simulation Models of Wood Dynamics (modified and updated from Gregory *et al.*, 2003).

Model	Model Type	Time Interval Modeled (yrs)	Time Step (yrs)	Stream Width (m)	Recruitment Mechanism	In-Stream Breakage	In-Stream Movement	Decomposition
Rainville *et al.*, 1986	Determistic	300	10		Forest mortality	No	No	No
Murphy and Koski, 1989	Determistic	250	1	8-31	Forest mortality/ bank erosion, slides	NA	In=out	Depletion rate§
McDade *et al.*, 1990	Determistic	NA	NA	*	Forest mortality	No	No	No
Van Sickle and Gregory, 1990	Determistic	Old growth	10	**	Forest mortality	No	In=out	No
Malanson and Kupfer, 1998	Stochastic	500	1		Forest mortality	No	No	No[d]
Benda and Dunne, 1997a,b‡	Stochastic	800-1,800	1	User defined	Forest mortality, fire mass wasting, bank erosion	No	Yes	Depletion rate
Minor 1997	Determistic	Old growth	NA		Forest mortality	No	No	No
Beechie *et al.*, 2000	Determistic	150	1	5-30	Forest mortality	No	No[a]	Number[e]
Bragg 2000	Stochastic	300	10	User defined	Forest mortality	Yes	Constant[b]	Constant[b]
Downs and Simon, 2001	Determistic	NA	1	6-20	Bank erosion	No	No	No
Welty *et al.*, 2002	Determistic	240	1	User defined	Forest mortality	No	User defined[c]	User defined[c]
Meleason *et al.*, 2003	Stochastic	500	10	100	Forest mortality	Yes	Yes	Decay[f]
Lancaster *et al.*, 2003	Stochastic	3,000	Range	User defined	Forest mortality, fire mass wasting, bank erosion	No	Yes	Decay

*First, second, and third order streams.
**Applied for two streams 12-15 m wide.
§Depletion rate through decay, breakage, and transport.
‡See also Benda and Sias (2003), Benda *et al.* (2002), USFS (2002).
[a]Output is depletion.
[b]Constant attrition of volume.
[c]Overall depletion user defined.
[d]Terrestrial not aquatic.
[e]Depletion rate.
[f]Decay rates until piece smaller than minimum.

framework for small and large streams may prove problematic because of limitations in their development. For example, attempts to apply the wood budgeting framework have been limited to assessments of wood recruitment (Martin and Benda, 2001; Benda *et al.,* 2002). These partial budgets have been constructed by examining changes in wood storage from newly recruited wood. Recruitment rates are then calculated based on mean ages of recruited wood. While the construction of these partial budgets does provide estimates of the rate of recruitment, the limitations of this approach need to be acknowledged. In particular, the assumptions made in the construction of partial wood budgets need to be validated (see Benda *et al.,* 2003).

Time scales for wood budgets are largely determined by study objectives and practical methods for estimating process rates and residence times. Difficulties in assessing long time scales likely present the greatest challenge associated with woody debris budgeting. The process rate is largely determined by local or regional forest dynamics, physiography, hydrology, and channel geomorphology. While chronic recruitment processes can be more easily observed and quantified (e.g., Young, 1994), difficulties arise in assessing the frequency and magnitude of episodic events important to headwater streams. This is particularly vital in regions where wood recruitment is dominated by extreme events (Swanson and Lienkaemper, 1978; Hogan, 1986; Johnson *et al.,* 2000a; May, 2002).

EFFECTS OF TIMBER HARVESTING AND RIPARIAN ZONE MANAGEMENT

Influence of Timber Harvesting on Wood Dynamics

The impact of timber harvesting and road constructions on wood dynamics in intermediate- and large size streams has been the focus of many studies in the PNW (e.g., Swanson *et al.,* 1984; Andrus *et al.,* 1988; Hartman and Scrivener, 1990; Ralph *et al.,* 1994; Hogan *et al.,* 1998). Much less work has been completed on small streams. Timber removal can influence the composition and abundance of wood entering headwater streams and hence affect the supply. Indirectly, logging adjacent to streams can influence the recruitment of wood by altering the hydrology (Moore and Wondzell, 2005) and the stability of slopes and banks (Benda *et al.,* 2005; Hassan *et al.,* 2005). In the short term, logging operations can also increase the supply of wood slash entering channels. In the PNW, a large number of studies have emphasized the acceleration of mass wasting processes following road constructions and harvesting (e.g., Gresswell *et al.,* 1979; Montgomery *et al.,* 2000; Brardinoni *et al.,* 2002; May, 2002). Much of the large wood entering stream channels does so through landslides and debris flow during large storm events (Nakamura and Swanson, 1993; Hogan *et al.,* 1998; Schwab, 1998; May and Gresswell, 2003a). Therefore, changes in the frequency and magnitude of mass wasting due to logging will significantly alter wood recruitment into headwater streams.

Theoretically, steep headwater streams have a high sediment transport capacity and therefore should not accumulate sediment that is much finer than the channel dimensions (Montgomery *et al.,* 1996; Church, 2002; Benda *et al.,* 2005; Hassan *et al.,* 2005). In-channel wood commonly forms logjams, which may retain sediment accumulations in otherwise bedrock channels (Heede, 1985; Benda, 1990; Montgomery *et al.,*1996; Massong and Montgomery, 2000; Montgomery *et al.,* 2003b), and even individual wood pieces can store significant amounts of sediment in headwater streams (e.g., Jackson and Sturm, 2002). Large wood in headwater areas may also prevent headward erosion of gullies and stream channels (Kelly *et al.,* 1995). On the other hand, in intensively logged areas, mass wasting events may have very long runout distances and can clean sediment from long lengths of stream channel (May, 2002). Therefore, changes in the characteristics and amount of wood delivery to headwater streams may transform sediment deprived systems to sediment filled systems, and vice versa.

In small streams the overall frequency of logjams commonly increases initially after logging, with most logging debris stored in relatively large, but infrequent, logjams (e.g., Bryant, 1980, Hogan, 1986). A decade after logging, Bryant (1980) reported that the channel of Maybeso Creek in Alaska was still dominated by large but less frequent logjams (Bryant, 1980). Both Bryant (1980) and Hogan (1986) suggest these changes result in an overall reduction in channel stability as large accumulations of sediment stored behind relatively unstable logging debris are more likely to fail during high flows than their unlogged counterparts, and this can lead to a sudden and widespread redistribution of channel sediments.

However, the pattern of channel adjustment is variable and may depend on channel type, particularly in small channels where both drag and buoyant forces acting on a log (as described by Braudrick and Grant, 2000) are insufficient to move or float logging debris. This may be especially relevant in step pool streams with high relative roughness and frequent local shallows and nonalluvial obstructions. For example, Millard (2001) found that logging debris remained stable during high flows in small channels up to 2 m in width, regardless of slope, while Bird (2001) observed relatively small and frequent logjams in step pool channels a decade after streamside logging. Furthermore, in the absence of landslides and debris flows, wood pieces (including logging slash) may persist at least 50 to 100 years because flows in these small headwater channels are too small to transport large amounts of wood (e.g., Gomi *et al.,* 2001).

A summary result of the impact of timber harvesting on wood inputs is presented in Table 5. For comparison, results for higher order streams (Washington studies) are also presented. Both an increase and a decrease in the number and volume of wood pieces after logging have been reported (Table 5). Conflicting findings for the effect of logging on wood recruitment can be attributed to: differences in the size distribution of wood; differences in time after logging; changing in management guidelines (e.g., slash removal and riparian buffers); and variations in management practices (operational methods).

Influence of Riparian Zone Management on Wood Dynamics

Riparian management guidelines have been significantly changed over the past 20 years because of concerns over fish and wildlife habitats (Bisson *et al.,* 1987). In fact, under current forest management practices, input of wood in fish bearing streams during logging activities is minimized compared to practices prior to the 1970s as reported by Froehlich (1973). Riparian buffer zones have been used to minimize the impacts of logging by protecting physical and biological stream processes. Ideally, riparian buffer zones maintain the level of natural input of wood and reduce excess recruitment of wood during harvesting activities; however, they rarely extend up into very small streams because most guidelines are designed to protect forests immediately adjacent to fish bearing streams.

Riparian vegetative buffer reserves are typically applied to fish bearing

TABLE 5. The Effect of Timber Harvesting and Riparian Management on the Recruitment of Wood in Streams.

Effect	Processes	Variable	Type of Logging	Change in Rate* (percent)	Duration**	Channel Width (m)	Location	References
Logging	Logging slash recruitment	Numbers and volumes	Clear-Cut 1	200-1,000	Immediate	0.5 to 15	Oregon	Froehlich (1973)
			Clear-Cut 2	40 to 200	Immediate	0.5 to 15	Oregon	Froehlich (1973)
			Clear-Cut		Immediate	2 to 3	British Columbia	Millard (2000)
			Clear-Cut 1	300	Immediate	1.4 to 6.0	Alaska	Swanson *et al.* (1984)
			Clear-Cut 1	150	3 years	0.8 to 1.3	Alaska	Gomi *et al.* (2001)
			Clear-Cut 1	150	40 years	0.6 to 1.2	Alaska	Gomi *et al.* (2001)
	Decrease recruitment		Clear-Cut	54	5 years	2 to 5	Alaska	Murphy *et al.* (1986)
			Clear-Cut	14	50 years	2.5 to 7.8	Oregon	Andrus *et al.* (1988)
			Clear-Cut	59	5 years	~15	Washington	Bilby and Ward (1991)
			Clear-Cut	50	40 years	~15	Washington	Bilby and Ward (1991)
			Clear-Cut	77	5 years	~5	Washington	Bilby and Ward (1991)
			Clear-Cut	56	40 years	~5	Washington	Bilby and Ward (1991)
			>50% removal	~50	< 40 years	< 10 m	Washington	Ralph *et al.* (1994)
Riparian Buffer	Wind throw			120 to 150	1 to 3 years	1.0 to 5.7m	Washington	Grizzel and Wolff (1998)
	No effect		26 to 54 % removal	100	6 to 17 years	2.1 to 6.1 m	Oregon	Carlson *et al.* (1990)
	No effect		< 50% removal	100	< 40 years	3 to 18 m	Washington	Ralph *et al.* (1994)

*Change in rate was estimated based on continuous measurement of wood accumulation or the paired analysis between logged and unlogged channels.
** Duration implies time from occurrence of timber harvesting to measurement of wood.
Note: Clear-Cut 1 implies logging using free falling and cable yarding method, whereas Clear-Cut 2 means logging using cable assist directional falling and cable yarding method.

streams and are often 20 to 30 m wide on channels that range in width from 2 to 100 m (Young, 2000). The Oregon Forest Practices Rules require a 15 m Riparian Management Area on small fish-bearing streams. Calculations showed that 51 percent of the trees retained within the riparian management zones (15 m buffer) could provide large wood to larger streams (Young, 2000). Reid and Hilton (1998) suggested that one tree height could sustain about 96 percent of the potential wood source for stream channels. However, tree fall within a buffer is frequently triggered by trees falling from upslope of the buffer zone (Reid and Hilton, 1998; May and Gresswell, 2003a). Riparian reserve zones can be highly susceptible to wind throw caused by changes in wind speed and direction due to edge effects at the boulder of the buffer (Chen *et al.,* 1995). Reid and Hilton (1998) found that buffers interlaced in recent clear-cuts could have double the tree-fall rates compared to older stands. Both short term (e.g., accelerated wind throw) and long term (e.g., senescence of older trees) rates of wood recruitment need to be considered to more fully understand the role of riparian management on wood dynamics.

Because a large volume of wood stored in small streams is derived from landslides that occur far upslope of channels (May and Gresswell, 2003a), the same narrow buffer zone applied to larger stream channels may not be adequate for maintaining wood inputs to headwater streams. The issue of buffer zone width and the extension of riparian buffers into intermittent or ephemeral, nonfish-bearing streams must be evaluated if the effects of forest management are to be thoroughly assessed.

KNOWLEDGE GAPS FOR FUTURE RESEARCH

In spite of the growing amount of research on the influence of wood on the channel dynamics of small streams, many knowledge gaps persist. In particular, very little is known about the role of mass wasting on wood recruitment and storage, relative to other processes such as bank erosion and mortality in small streams. For example, although computer simulations for the Oregon Coast Range suggest that mass wasting contributes approximately 10 to 15 percent of total recruitment (Benda and Sias, 2003), this estimate is much lower than empirical studies have documented (May, 2002; May and Gresswell, 2003a; Reeves *et al.,* 2003).

A second knowledge gap surrounds the relative importance of different wood depletion processes, especially those associated with wood transport. Effective field studies undertaken over the requisite multiple decades to centuries are not feasible, and there are virtually no detailed wood depletion models applicable to small channels. Wood loss to fans or valley bottoms, including loss to burial and subsequent exhumation, needs accounting as part of a full wood budget. Wood is also lost to decay, but the relative importance of terrestrial and aquatic decay rates for wood submerged for only a portion of each year in a small channel are unknown. For instance, are stages of decay quantifiable and discrete in time? Additionally, it is necessary to understand the role of abrasion in conjunction with fluvial and colluvial transport of boulders in steep channels.

Generally, ecosystem type affects the quality and quantity of wood available to a channel, while the spatial and temporal variability of wood recruitment, storage, and loss depends on variations in hydrology, forest type, and dominant erosion and transport processes. However, the effect of these variables as they change locally across a watershed (from valley bottom to mountaintop) or regionally across the landscape (from maritime to continental climates) is largely unknown and represents a third major knowledge gap. A related issue involves developing a better understanding of wood recruitment processes as influenced by ecological disturbance regimes (Nakamura and Swanson, 2003).

A fourth knowledge gap concerns the effects of management practices on wood quantity, structure, and movement in small streams. This includes a more complete understanding of the rates of post-harvest wood delivery and the size distribution of individual pieces relative to those that are easily transported and redistributed to downstream reaches. These questions necessarily depend in part on the understanding of how management affects all parts of the fluvial system, including changes to flow and sediment transport regimes in small watersheds.

Finally, Swanson (2003) suggests a landscape framework for examining linkages of the wood regime in both natural and managed watersheds over broad temporal and spatial scales. He asserts that a landscape perspective is one of the major gaps in knowledge. Although significant progress has been made at the fine spatial and temporal scales of wood dynamics in streams (despite the knowledge gaps identified above), little has been done on the reach and basin scales and on longer time scales (Swanson, 2003). This lack of knowledge imposes a major limitation on the understanding of wood in streams and the influence of wood on ecosystem function for both proximal and distal ecosystems.

CONCLUDING REMARKS

In-channel wood in forested, small streams influences channel morphology, regulates sediment transport and storage, and alters flow hydraulics. In these headwater channels wood tends to accumulate, sediment is stored upstream of the accumulation, and this can transform steep bedrock channels into alluvial reaches. In these streams, wood influences channel morphology by regulating the temporal and spatial character and the quantity of sediment stored within the channel zone, and this in turn affects channel stability and downstream sediment and wood fluxes.

Wood is recruited to the stream through a variety of hillslope and channel processes. In mountainous headwater streams, wind throw, insect and disease outbreaks, timber harvesting, wasting processes, fire, and tree mortality dominate wood delivery to channels. Wood recruitment rates from these processes are episodic and highly variable in space and time. Fire is likely to affect the wood budget by altering the age structure of the forest, initiating episodic pulses of wood recruitment, and influencing the mobility of instream wood. The impact of episodic wood supply on channel morphology remains poorly understood and needs to be addressed in future research. Another issue is the magnitude and frequency aspects of wood delivery and how this affects sediment yield. Because large episodic inputs of wood to a stream can increase sediment retention and cause channel destabilization, sediment yield can shift to larger-magnitude releases at longer recurrence intervals.

Wood is stored for various durations at the base of hillslopes, on fans, in floodplains, and within the channel. Difficulties in assessing wood storage in small streams can arise from unclear definitions of what constitutes wood stored in the stream. Wood is transferred out of the fluvial system by downstream transport or lost through abrasion or in-situ decomposition. Log stability in channels is controlled by wood piece dimensions relative to the channel, attached root wads, and degree of anchoring in the channel bed and bank. Log movement is more likely to occur as channel size increases and when logs are shorter than bankfull width, implying that fluvial transport of wood is significant in higher order streams. Wood decay, including decomposition, abrasion, and fragmentation, has an important influence on the instream function of wood. However, wood decay processes and rates remain poorly understood and need to be addressed in future research.

Modeling of wood dynamics through the channel network is an important tool for forest management. In the past three decades, a range of models has been developed in various spatial and temporal scales. Benda and Dunne (1997a,b) and Lancaster *et al.* (2003) models incorporate a range of wood input processes, making them flexible modeling frameworks for headwater streams. Also, the wood budget is a flexible conceptual framework that can be used to study wood dynamics in small and large streams. Due to lack of field data needed to test the developed models under a range of environments, the usefulness of current models is limited.

Forest management in small, forested basins is likely to change water, sediment, and wood inputs to channels and significantly affect channel morphology, channel stability, and aquatic habitat. Harvesting practices and road designs on relatively steep unstable slopes can lead to changes in the amount and characteristics of wood supplied to channels and the amount and texture of sediment inputs. Better harvesting practices and road design are likely to reduce the impact of logging on wood supply and characteristics, reduce channel instability in low order streams, and consequently reduce impacts to sediment and wood delivery to higher order streams.

In spite of the growing research on the influence of wood on channel dynamics of small streams, many knowledge gaps impose serious limitations on field and modeling programs in the context of land management. One of the main problems of measuring and predicting the influence of forest management practices is that monitoring programs in most forested areas are typically too short to sample the variability of natural and disturbed hydrological regimes, increasing the likelihood of missing significant wood and sediment mobilization events (Dunne, 2001). This suggests that earlier questions concerning the effects of management practices on wood structure, quantity, and movement in small streams (and large streams) may still be unsolved. In order to make progress, well-designed long-term field programs are needed that pay appropriate attention to spatial variation of hydrological and geomorphological processes in the landscape (Dunne, 2001). In this context, Swanson's (2003) suggested landscape framework for examining linkages of the wood regime in both natural and managed watersheds over broad temporal and spatial scales is worth pursuing.

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