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Wood in Rivers: A Landscape Perspective

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Abstract.—A landscape perspective of wood in world rivers accounts for spatial and temporal patterns of sources of wood from streamside forests, processes of wood delivery to channels, transport of wood through river networks, and trapping sites of wood. Amounts of wood in a river system also depend on productivity of forests in source areas and decomposition rates. Collectively, these factors determine the amount and arrangement of individual pieces and accumulations of wood through a river network, which, in turn, affect ecological, geomorphic, social, and other features of rivers. Research to date deals with subsets of these components of wood in rivers, but there has been limited development of a general framework for wood in river networks. This chapter considers a framework for examining the arrangement of wood in river landscapes and how it may reflect the history of spatial patterns and timing of wood input and redistribution. Field studies provide examples of different spatial patterns and architectures of wood accumulations. Wood accumulations are shaped by input processes, trapping sites, and transport processes. Reaches in river networks may switch from wood patterns dominated by one set of controls to another because of gradual or abrupt input and redistribution. A framework for future studies and management includes interpretation of these different controls through time and over river networks.

Introduction

The physical dynamics and ecological significance of large pieces of wood (>1 m long and >0.1 m diameter) in river systems have strong landscape properties. "Landscapes" are land surface areas composed of units or patches of differing geophysical and biological properties (Risser et al. 1984; Forman and Godron 1986). Landscape studies commonly encompass an adequate sample of landscape units, examine spatial units within the study area explicitly, and consider time scales sufficiently long to reveal representative patterns in landscape conditions and change. Patterns and dynamics of wood in rivers include forest-stream interactions scaled up from local sites to full watersheds, effects of the network structure of streams and riparian zones, and interactions among input, transport, and accumulation of wood in different types of river systems. Furthermore, studies can focus on pattern-process relations of wood itself or on the ecological, environmental hazard, or other consequences of those patterns and processes.

Little work to date explicitly considers landscape aspects of wood in rivers, especially the arrangement of wood pieces and accumulations over widely differing stream sizes and types, although attention to these topics has grown in recent years. This paper addresses the current state of knowledge about landscape aspects of wood in rivers, identifies knowledge gaps, and offers a framework for further work to benefit science and management. The emergence of landscape perspectives in studies of wood in rivers is reflected in many chapters in this book.

State of Knowledge

Existing published and unpublished works touch only lightly on landscape perspectives of wood in rivers. Many chapters in this book provide a conceptual framework for analysis of sediment and wood delivery and routing through river networks. Most published work on standing crops of wood in streams has focused on relations to forest age and management history, and ecological effects (see reviews of Harmon et al. 1986; Bisson et al. 1987; Bilby and Bisson 1998). Existing work is largely at either a local scale, such as work in small streams, or adopts a generalized, broad perspective, such as compilations of samples of standing crop measurements over longitudinal profiles of rivers (such as Harmon et al. 1986; Bilby and Ward 1989). New studies, however, are taking a much more comprehensive view than existed a few years ago (Benda and Dunne 1997a, 1997b; Martin and Benda 2001).

In working at any particular scale, such as the landscape, drawing on information relevant to system behavior must be considered at the full range of scales. Integration of knowledge about wood in rivers from the local site to the full river network is essential (Frissell et al. 1986; Gregory et al. 1991) and in even broader geologic-tectonic (Montgomery 1999) and biogeographic (Harmon et al. 1986; Montgomery 1999) contexts. Temporal perspectives, including stochastic aspects of system behavior, are also integral to understanding system behavior (Reeves et al. 1995; Benda and Dunne 1997a, 1997b). Geologic context influences the amount and size distribution of sediment in rivers and the associated landforms, hence the geophysical dynamics of the system. Biotic context of the landscape determines forest composition, structure, productivity, and dynamics of a landscape. Together, the geologic and biotic components determine the amount, size distribution, and persistence of wood in river systems. In this discussion, wood dynamics in rivers are considered at the scales of constrained-unconstrained stream reaches (sensu Grant and Swanson 1995), longitudinal river profile (sensu Vannote et al. 1980), and the full river-riparian network in a forest landscape.

A general framework—wood in a landscape perspective

The basic elements of wood movement through landscapes are the river network, the surrounding forests, and the processes that link them (Figure 1). Forests are dynamic in response to disturbance and successional processes. Patterns of

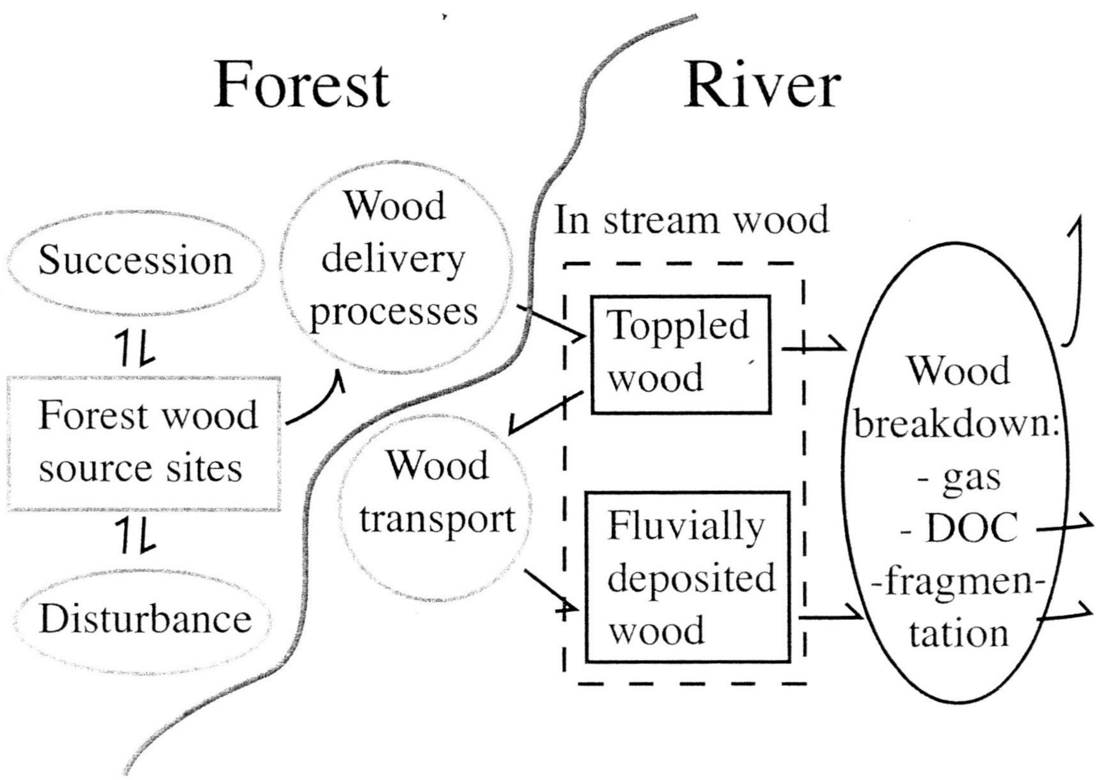

FIGURE 1. Stores (boxes) and transfer processes (circles) for routing of wood from forest sources to and through river systems.

wood movement follow gravitational flow paths from forest to stream by wood delivery processes and then potentially down rivers by fluvial wood transport processes. Wood is deposited at persistent or ephemeral accumulation sites along rivers, forming "standing stock." Wood in storage is subject to decomposition, resulting in release of gases to the atmosphere and dissolved organic carbon and other constituents that move downstream. Physical abrasion of wood produces fine fragments of organic matter that also move downstream, but are no longer in the large wood category.

A spatially explicit landscape approach considers landscape structure, including the types and arrangement of landscape units that affect wood supply (the forest patchwork) and transport and storage (the stream network); processes that vary in relation to position in the stream and riparian network; and concepts related to how these structures and processes change through time (Figure 2). The basis for these observations comes from conceptual, empirical, and modeling approaches (Keller and Swanson 1979; Gurnell et al. 2002; Abbe and Montgomery 2003; Benda et al. 2003, this volume).

The primary **landscape structure units** in this analysis are patches of vegetation that serve as sources of wood and the stream network itself where material is transported and deposited. Secondary features of potential significance include natural landforms, like alluvial fans, and engineered structures, such as roads, channelized stream reaches, and dams, that may alter the movement of wood through landscapes. Roads, for example, can be initiation sites of landslides that deliver wood to streams, and they may block passage of wood being transported by debris

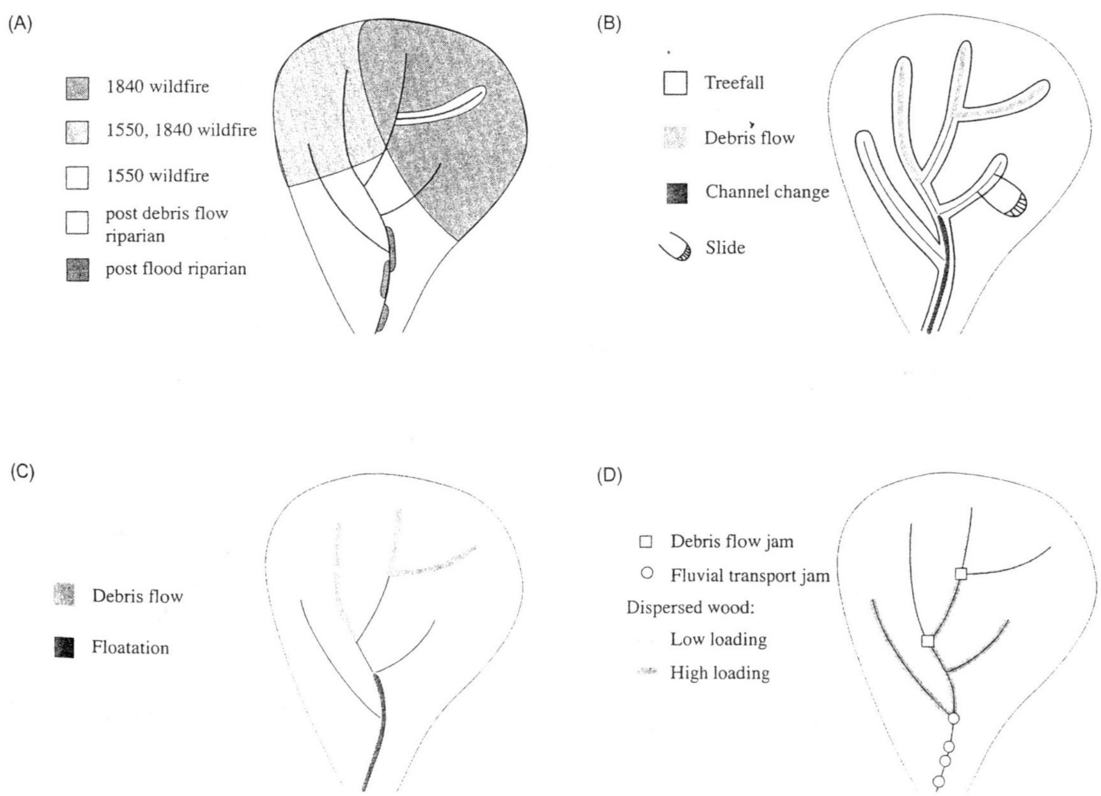

FIGURE 2. Schematic map of (A) forest disturbance history and resulting patchwork showing upland and riparian forest age-classes and stand-initiating processes; (B) zones influenced by different processes of wood delivery to channels; (C) zones of wood transport processes in streams; (D) patterns of wood accumulations in a stream network.

flows or flotation (Wemple et al. 2001). The **source area** of wood for rivers is the adjacent forest landscape whose structure reflects the history of terrestrial disturbance events, like fire and windstorm, and river-based events, such as debris flows, floods, and lateral channel change (Figure 2).

Processes that control the input and redistribution of wood vary with position in stream networks (Keller and Swanson 1979; Montgomery 1999; Martin and Benda 2001; Benda et al. 2003; Gurnell 2003, this volume). A landscape can be mapped as zones (or "process domains," in the language of Montgomery (1999)), in which different wood input and transport processes operate (Figure 2B and C). Some source areas and delivery processes disperse wood through time and space, such as chronic mortality in streamside forests in response to small-scale gap dynamics and competitive interactions among trees. Other processes deliver batches of wood from discrete source patches. Source patches and delivery processes may persist in locations or be transient, shifting locations through time. For example, wood delivery, both dispersed and in batches, comes from the streamside zone of a tree-height width where toppling of all or parts of live and dead trees is an important delivery mechanism (Figure 2B). Other processes, like landslides and snow avalanches, have the potential to deliver wood from areas farther upslope.

Transport processes move wood downstream through a river system, and different processes dominate in different parts of the network (Figure 3). Debris flows, for example, are relegated to small, steep channels. Flotation, a dominant transport process in large channels, can move wood in either a congested (batches of interacting wood pieces) or an uncongested (individual pieces) manner (Braudrick and Grant 2000). A potentially large, but unknown, fraction of wood in rivers leaves the system via decomposition as CO_2 or fine particulate matter, not as large wood pieces.

Patterns of wood sources and processes of input and transport also interact with channel and valley floor features to determine **wood accumulation sites**, which result from either lack of transport capacity or the presence of trapping structures (Gurnell et al. 2002; Abbe and Montgomery 2003). Trapping structures may be geomorphic, biotic, or hydraulic features. Wood can accumulate where a channel shallows or narrows, on obstructions in channels and along their margins, or stranded anywhere as flood flows drop.

The **standing stock**—the amount and arrangement—of wood in a river system is a reflection of this complex array of both dispersed and discrete input processes and events that redistribute wood (Gurnell et al. 2002; Abbe and Montgomery 2003). The standing stock of wood in a river reach is commonly composed of material that fell into place from the neighboring forest source area and other material that was transported into place by streamflow or other transport processes. This distinction can be useful in interpreting the history of processes affecting a site as well as the architecture of wood assemblages and their associated functions, such as pool formation, sediment trapping, and habitat for terrestrial and aquatic organisms. Given a certain amount of topographic and forest landscape control on source-sink relations, the pattern of standing crop of wood through a river network may be somewhat predictable (Figure 2D). An important temporal factor for interpreting standing crops of wood is the time since the last input and redistribution events. Immediately after a flood, for example, deposition of mobile wood by fluvial processes would be expected. In the same river reach after a wood movement event, some wood pieces will fall into the river and lie where they fell. This material may be more vulnerable to transport than wood pieces of the same size and shape that had been transported and deposited in more persistent depositional sites, such as lodged against massive boulders, bedrock outcrops, or stable trees.

The following illustrations of some of these points and conjectures come largely from the relatively well-studied rivers of the Pacific Northwest of the United States, but the phenomena are discussed in general terms. These examples reflect certain biases, such as large quantities of large pieces of wood and the transport processes characteristic of some montane environments. The approach of thinking in terms of patterns, processes, and controls is integral to landscape perspectives, however, and transferable to other geographic areas.

Landscape aspects of wood sources

The geography of forests as sources of wood to rivers is defined by the area potentially subject to wood input. Thus the map of wood delivery is the overlap of the forest patchwork map (Figure 2A) and the map of zones influenced by different modes of potential wood delivery (Figure 2B). Multiple processes, each with characteristic lat-

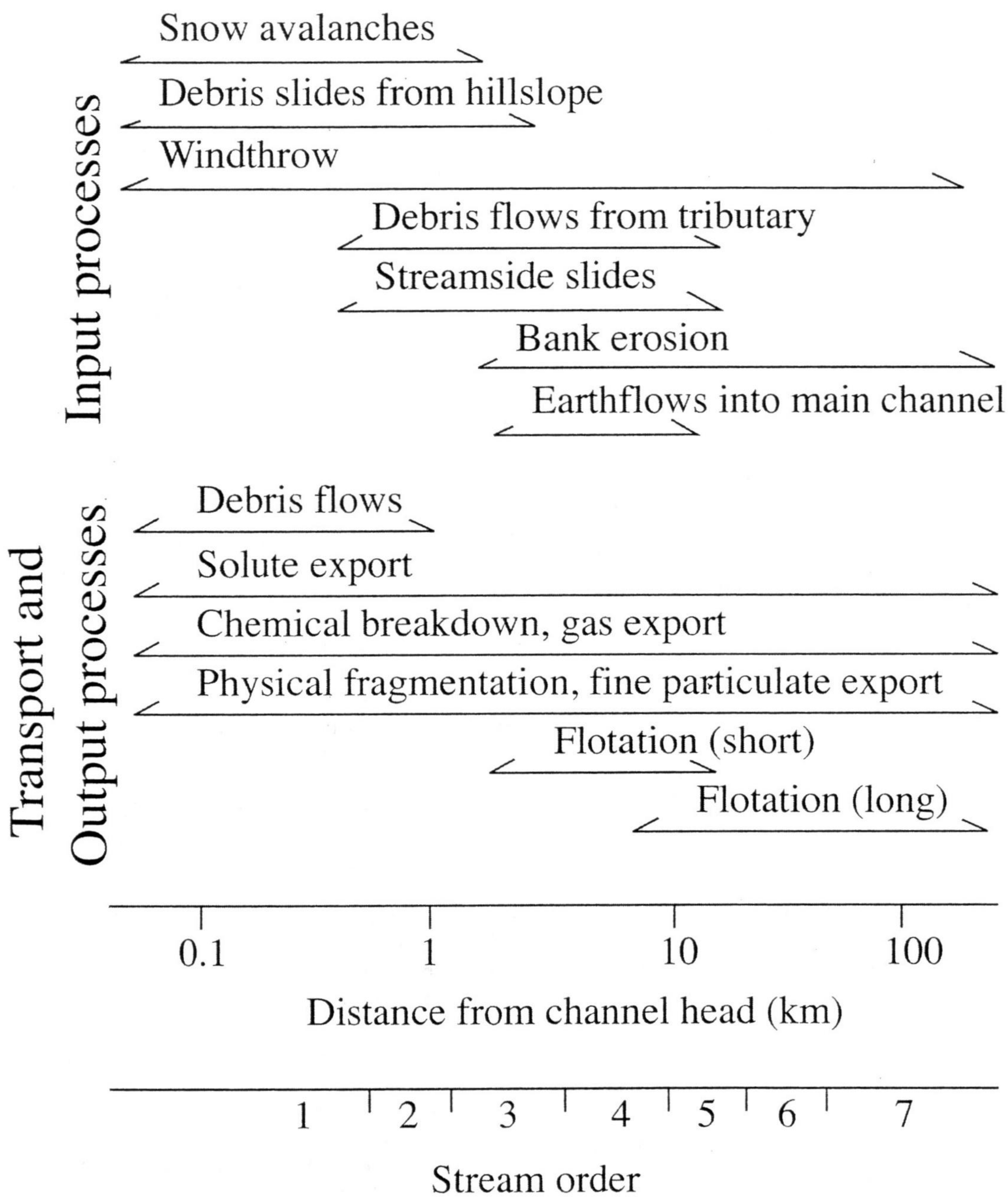

FIGURE 3. Schematic distribution of wood input, transport, and output processes in an Oregon Cascade Range river (adapted from Keller and Swanson 1979). Some processes, such as windthrow, are more significant in upstream areas, and other processes are more common in downstream areas. "Short" flotation transport refers to movement of pieces with lengths of 0.5–1.0 bank-full width that can commonly move distances of 10 s to a few hundred meters, which is the channel length that would include several wood accumulations. "Long" flotation transport refers to the potential for such wood pieces to move a kilometer or more as a single, floating piece.

eral extent away from the channel, can deliver wood to any particular stream reach (Figure 2C). The suite of processes that affect wood distribution in stream reaches varies down the stream system (Keller and Swanson 1979; Figure 3). Of course, bioregional and physiographic factors also affect the presence and absence and relative rates of input, such as snow avalanches and river ice movement operating in cold regions, and the undercutting of riverbanks, which is more common along large, low-gradient tropical rivers.

Commonly, riparian vegetation grows in narrow, linear patches along streams in response to the history of floods creating gravel bars on accreting portions of channel bends or sites of repeated disturbance and reestablishment of forests. Where the width of riparian vegetation patches is less than the height of adjacent forest, a form of lateral and vertical stacking of wood sources sometimes allows two or more types of riparian and upland forest to serve as wood sources for a given stream site (Swanson et al. 1990).

Several processes alter the rates of wood delivery from streamside forests (Naiman et al. 1993; Acker et al. 2003). Gradual processes of forest succession change the species composition, size distribution, and amount of wood delivered to streams. Abrupt disturbance of streamside forest may result in a pulse of wood input to streams, such as by wind-toppling of streamside forest, followed by reduced input while the stand is reestablishing. Clear-cutting of streamside forest removes wood sources without delivering a pulse of wood to the stream. Thus, negative feedback mechanisms can reduce input of wood to streams for decades or even centuries until the disturbed sites reestablish and produce large wood. In areas where disturbance is more frequent than the time required for trees to grow to the size-class of large wood, streamside vegetation may not produce large wood for long periods.

Landscape aspects of wood transport and accumulation sites

In many river systems, the significance of different processes of wood transport varies substantially through the river network as a result of geographic variation in size and amount of wood delivered to the channel and the capacity of the river system to transport wood. **Flotation**, for example, is constrained by the relations of channel width to wood-piece length and water depth to piece diameter—relatively small pieces are more mobile (Lienkaemper and Swanson 1987; Bilby and Ward 1989; Braudrick and Grant 2000). Therefore, based on these perspectives from ecosystems dominated by conifers, river systems with increasing flow in the downstream direction are expected to exhibit increased significance of flotation in lower river reaches. In deciduous forests, however, tree form is commonly broadly branching, so fallen deciduous trees with large limbs may be less susceptible to transport than cylindrical pieces with the same wood volume, particularly in low-velocity rivers (for example, Palik et al. 1998).

Debris flows, the rapid, downstream movement of 100 s to 1,000 s of m^3 of soil, sediment, and wood, provide a contrasting example of landscape influence on wood dynamics common in montane river systems. Debris flows flush sediment and large wood from small, steep, confined channels (Figure 3b in Swanson et al. 1998) and deposit it in lower gradient, less confined sites, such as alluvial fans, floodplains, and fourth-order and larger channels, or at channel junctions with abrupt change in flow direction (Benda and Cundy 1990). The resulting deposits can form large jams that greatly exceed channel dimensions or, in the case of delivery to large channels, the wood may be scattered in smaller accumulations down the main channel (Johnson et al. 2000).

A 50-year record of debris flows in the Blue River watershed of the Oregon Cascades provides examples of several aspects of debris flow influence on wood distribution across a stream network (Snyder 2000). The documented debris flows are restricted to first- through third-order channels and in low elevation parts of the landscape, which are characterized by steep slopes, slide-prone soils, and high water input to soils during rain-on-snow precipitation events (Swanson and Dyrness 1975; Swanson et al. 1998; Snyder 2000). The net effect is that a large percentage of the length of small streams in the debris flow-affected, lower-elevation half of this study area was flushed of wood accumulated over the previous 100 years. The upper-elevation half of the study area, however, has been much less affected by debris flows and wood transport.

Debris flows are episodic events in most landscapes. For example, most debris flows in the 50-year record for Blue River were in just two winters. About half of the inventoried events took place in the winter of 1965, and about 30% of the debris flows occurred during one flood in 1996. Some of the 1996 debris flows rescoured channels that had not yet completed reloading with wood after debris flows in the same channels in the winter of 1965. Presence of forest roads and clear-cut areas substantially increased the number of debris flows but did not alter the general pattern (Swanson and Dyrness 1975). Wood abundance in channels can take more than a century to recover, as indicated by dendrochronologically documented residence times of large wood in channels (Swanson et al. 1976; Keller and Tally 1979; Hyatt and Naiman 2001).

Some wood movement from hill slopes to small streams to large rivers can be viewed as a sequence of processes, that Nakamura et al. (2000) term a **disturbance cascade**. Wood transport begins as debris slides on steep hill slopes, transforming into debris flows down steep, headwater channels, and potentially traveling to larger channels where the wood moves by flotation. Events in the 1996 flood affecting the Blue River watershed provide examples of this sequence (Nakamura et al. 2000; Nakamura and Swanson 2003, this volume). In the 1996 flood in Blue River, only 22 of 39 debris flows delivered wood to fourth- and fifth-order channels, and the remainder stopped in smaller channels (Nakamura et al. 2000). A variety of geomorphic and engineered features and large, standing trees along the flow path can interrupt delivery of wood and sediment to large channels (Wemple et al. 2001). Roads, for example, were involved in stopping the movement of 28% of the debris flows in the 50-year record in Blue River (Snyder 2000).

Wood accumulation sites may be distinctive to the transport process that produced them and the location in the stream network (Gurnell et al. 2002; Abbe and Montgomery 2003). Development of effective trapping sites varies among river systems. For example, simple, straight channel form may facilitate efficient movement of wood downstream, but complex, braided river channels exhibit low wood transport efficiency. Some types of trapping sites persist for many millennia and others may be ephemeral, like single large trees. Wood transported by debris flows tends to accumulate in sites of decreased channel gradient and increased width—often associated with obstructions, such as large standing trees or road fills. In channels wide enough to transport most wood pieces present, a variety of channel margin and secondary channel features retain transported wood (Nakamura and Swanson 1994; Gurnell et al. 2002; Abbe and Montgomery 2003; Gurnell 2003). Along large rivers wood accumulates persistently on the heads of large bars or islands, in the mouths of secondary channels, along the riparian forest fringe where flow enters the floodplain, at the confluence of major rivers where the flood crest of one river creates a backwater effect in the mouth of the other, and in other sites of diminished transport capacity (Gurnell et al. 2000; Piégay and Gurnell 1997; Abbe and Montgomery 2003). River meandering and channel avulsion play critical roles in these processes of wood input and redistribution in low-gradient rivers (Piégay et al. 1999; Piégay 2003, this volume).

Properties of stream networks may influence the effects of certain processes on wood distribution. For example, the role of debris flows in delivering wood to fourth- and fifth-order channels and valley floors may be accentuated in networks that are elongate and have numerous debris flow-prone tributaries. In such basins, a higher proportion of channel junctions may have the potential to deliver wood by debris flows than more dendritic channel networks. The potential for wood transport by debris flows through a network depends in part on network properties, such as junction angles and channel gradient (Benda and Cundy 1990), and also on valley-floor landforms. Debris flow deposition of wood jams at the confluence of second- and fifth-order channels, for example, may result from landforms, such as alluvial fans, rather than the junction angle readily interpreted from topographic maps (Snyder 2000).

Landscape aspects of standing stock of wood in rivers

Patterns of the amount and locations of wood in rivers reflect interactions among input, redistribution, and loss. Spatial patterns of wood in river systems can be addressed at a series of nested scales—variation down the longitudinal profile of a river, variation with respect to position in the river network, distribution of accumulations in a river reach, and location of pieces within individual accumulations. At the finer scales, wood characteristics include the degree of aggregation, the architecture of accumulations, and degree of burial in sediment.

The River Continuum Concept (Vannote et al. 1980) provides a useful conceptual framework for understanding riverine ecosystem structure and function along a longitudinal gradient from headwaters to river mouth. Both reduced inputs and increased transport capacity may be responsible for observed downstream decreases in standing crop of wood (Naiman and Sedell 1979; Harmon et al. 1986; Bilby and Ward 1989). Few workers, however, have studied both small streams and large rivers in a single basin with compatible sampling methods, although Martin and Benda (2001) offer an interesting step forward on this issue. The simple, longitudinal depiction of wood along the river continuum reveals a relatively high standing stock per unit area in headwater streams in response to high input rates from the surrounding forest and the limited transport capacity of the stream.

Arrangement of wood in river networks has been hypothesized to exhibit increased aggregation in the downstream direction, based on assumptions about the controls of source area, transport capacity, and distribution of trapping sites (Swanson et al. 1982; Benda et al. 2003). In headwater streams, wood tends to lie where it fell from the adjacent forest because of the limited transport capacity of small streams, except when and where debris flows can mobilize large volumes of wood. A clumped pattern is produced by localized sources in sites of limited transport capacity, such as outside of meander bends undercutting forested riverbanks, resulting in wood accumulations on the heads of point bars. In large channels, transport by flotation can accumulate wood at trapping sites, such as the prows of islands and mouths of secondary channels (Gurnell et al. 2002; Abbe and Montgomery 2003).

Various features of wood pieces and their arrangement can be used to distinguish pieces that have fallen into place from those transported into place by stream flow (for example, Swanson et al. 1984). The distinction between pieces emplaced by fluvial transport and those located where they fell can be useful in interpreting recent processes and long-term dynamics of wood in stream channels.

The architecture of wood accumulations may be characterized by the degree of contact among pieces and their relative orientation (Abbe and Montgomery 1996, 2003). Trees that have toppled into a channel typically form open structures with abundant void space that can serve as habitat for terrestrial and aquatic species. Wood accumulations formed by fluvial deposition and debris flows are commonly assemblages of parallel, tightly packed wood pieces. In some situations, scour around wood pieces precludes burial in sediment, but at other times, such as with debris-flow deposits, wood structures facilitate their own burial. All these aspects of accumulation form affect function.

A typology of controls on wood amount and arrangement

Basic questions in the landscape analysis of wood in rivers are: What is the amount and arrangement of wood in a river system? What controls these features? How do they vary in time and space? A general framework, or typology, for examination of controls on arrangement of wood in rivers can be used in field and modeling studies and for planning stream habitat restoration projects. Such a typology of wood conditions can be based on distinguishing the relative influence of critical factors affecting the arrangement of wood in river reaches. Dominant critical factors are (1) input may be dispersed or patchy in time, space, or both; (2) discrete trapping sites may be strongly or weakly expressed; (3) locations of source and accumulation sites may be persistent or transient; and (4) transport distances may be long or short relative to the spacing of source or accumulation sites. Examination of forest and river systems with different wood dynamics provides examples of cases with different relative strengths of source areas, transport processes, and accumulation sites in determining the arrangement of wood in a particular river. Once we have defined a hypothetical typology of wood dynamics in rivers, it can be tested through field and modeling studies.

Four major types of controls on wood arrangement are identified:

Discrete-source-area control of pattern.—Arrangement of discrete source areas along a river dominates patterns of wood in the river where transport distances are much shorter than the spacing of source areas (Figure 4a).

Trapping-site control of pattern.—In systems with effective trapping sites, their arrangement dominates wood accumulation patterns where transport distances are long relative to spacing of source areas (Figure 4b, in the case where deposition sites are determined by presence of trapping sites).

Transport control of pattern.—In river reaches lacking discrete wood-trapping sites and where transport distances are long relative to source-area spacing, wood is randomly distributed, regardless of the pattern of

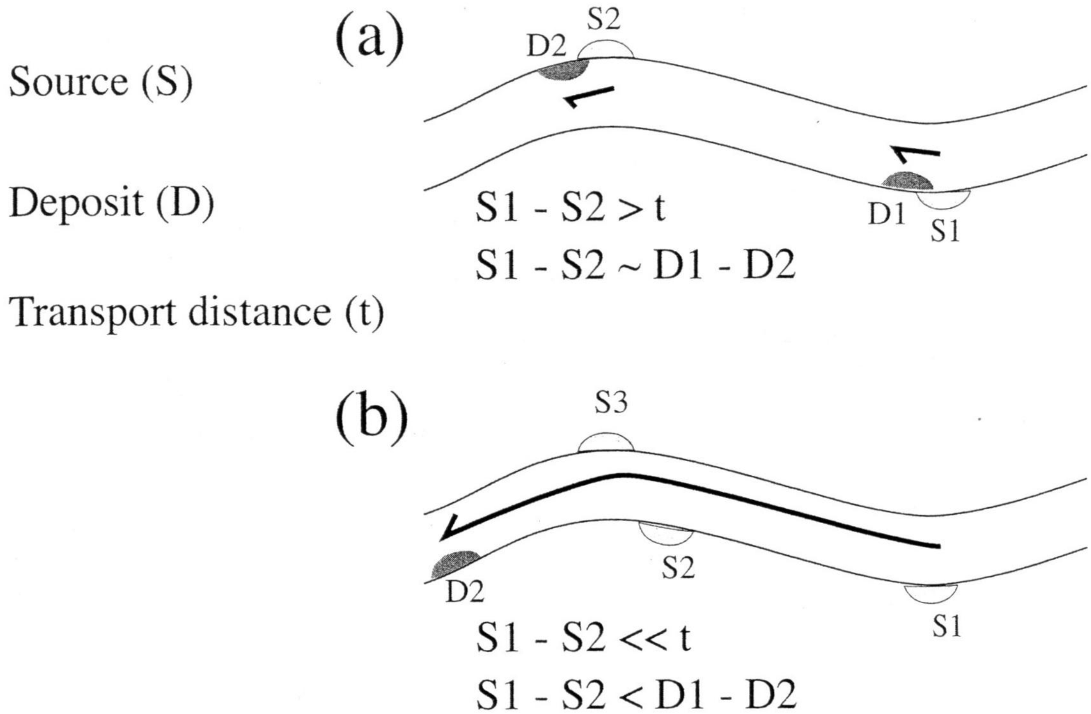

FIGURE 4. Hypothetical patterns of standing crop of wood in a river network when trapping sites are discrete: (a) transport distance is short relative to spacing of source areas, and (b) transport distance and spacing of deposition sites are long relative to spacing of source areas.

wood source areas and input processes (Figure 4b, in the case where deposition sites are determined by limits on transport unrelated to presence of a trapping site).

Dispersed-source control of pattern.—In areas of dispersed input and very limited transport capacity, wood is randomly distributed and amounts reflect forest stand and decomposition histories.

The history of wood input and redistribution is an important, additional dimension of controls on wood amounts and arrangements. Wood conditions in a site strongly reflect the relative and absolute timing of wood input, redistribution, and loss. The historical dimension of the arrangement of wood implies that individual sites may display different types of controls on wood conditions at different times. For example, a protracted period with dispersed wood input and no redistribution events may exhibit dispersed-input control. Immediately after a major flood, however, the site may appear to be an example of either transport or trapping-site control, depending on the strength of trapping-site influence. After an additional period of dispersed wood input, the site may exhibit a mixture of patterns produced by both input and transport. This history of wood dynamics may be reflected not only in the amount and arrangement of wood, but also in the distribution of wood-decay classes (Harmon et al. 1986) with the older, transported pieces in more advanced stages of decay than many of the recently input pieces. Clearly, placing the status of wood in a study reach or network in its historical context is critical.

Examples of types of wood dynamics

Only a handful of field studies have the temporal and spatial scope to explicitly shed light on the different types of wood-dynamic systems. A few field examples give a sense of how patterns of wood may reveal the hypothesized dynamics in particular types of systems.

The H. J. Andrews Experimental Forest in the Cascade Range of Oregon provides examples of wood dynamics in steep, mountain streams (Swanson et al. 1998; Snyder 2000; Swanson and

Jones 2002). Throughout much of the basin, wood input to small first- through third-order streams, in the past several centuries, has been dominated by dispersed tree fall, resulting in large accumulations of wood (Harmon et al. 1986). In parts of the basin where debris flows move wood, three types of wood accumulations are observed: (1) dispersed-source control pattern in channels without debris flows for a century or more containing wood where it fell; (2) transport control pattern in barren channels recently flushed by debris flows; and (3) trapping-site control pattern in wood jams in low gradient, wide stream reaches at the ends of debris-flow tracks where wood has piled up (Swanson et al. 1976; Snyder 2000). Small channels in parts of the basin without debris flow influence primarily exhibit the dispersed-source control pattern.

An apparently cyclical pattern of shifting controls on wood conditions is represented in a series of maps spanning nearly 20 years showing wood arrangement in a fifth-order reach of lower Lookout Creek in the Andrews Experimental Forest (Nakamura and Swanson 1993; Faustini 2000; Swanson and Jones 2002). The channel at this site is about 25 m (82 ft) wide; it has a drainage area of 62 km^2 (24 mi^2) and old-growth conifer forests bordering the channel. A 1978 map (Figure 24 of Swanson and Jones 2002) shows a channel with little wood, except in small patches apparently floated into place during floods in 1964, 1965, and 1972. In the 1980s and early 1990s, several large trees toppled from the streamside area and additional wood floated in from upstream, strewing the channel with a mixture of flood-deposited and toppled wood. A major flood in 1996 flushed much of the wood out of this stream reach and formed small accumulations along the channel margins, much like those observed in 1978. Thus, this stream reach may undergo cycles of increased complexity from input of dispersed wood (dispersed-source control of pattern), punctuated by flushing events and accumulations in trapping sites (trapping-site control) during floods with recurrence intervals of about 50 years and more. Land management activities, including roadbuilding, wood removal from streams, and forest cutting, have altered the amount, transport, and arrangement of wood in parts of this basin (Swanson et al. 1976; Snyder 2000; Swanson and Jones 2002).

An example of discrete-source-patch control on wood dynamics can be found in low-gradient, alluvial rivers. In a low-gradient coastal plain river, Palik et al. (1998) and Michener et al. (1998) found that a major flood toppled 22 trees/km into Ichawaynochaway Creek, Georgia, but the wood did not move significantly downstream from the source area during this or subsequent floods. Wood input was highest in the more constrained stream reaches where current velocity was interpreted to be the greatest and as having high potential to topple trees. No trees greater than 20 cm dbh moved more than a few meters. Therefore, the pattern of wood deposits was controlled by the pattern of wood source areas because, despite flooding, transport was so limited.

Gurnell et al. (2000, 2002) presented an example of wood distribution dominated by trapping-site control. The Fiume Tagliamento, Italy, is an unconstrained river bordered by woodlands serving as the source of wood for the river. Wood along the river tended to be concentrated in areas of complex channel pattern, on exposed gravel bars, and at the heads of islands. Newly developed islands had greater amounts of trapped wood than older, established islands. Exposed gravel in multiple-thread channels had six times the wood amount as exposed gravel areas in single-thread channels. Thus, trapping sites showed variation in both the stage of island development and the context of channel form.

In each of these examples, it is appropriate to ask if the patterns observed represent long-term system behavior or are a narrow reflection of the most recent events. Some systems have stable properties of wood inputs, and others may be quite variable, which affects the strength of inferences drawn from a single sampling. Modeling and long-term field studies are needed to test and develop a more extensive and rigorous typology of wood system dynamics at multiple scales and to explore its usefulness in research and restoration. A greatly expanded set of field examples in diverse settings with longer records would be instructive.

Knowledge Gaps

A landscape perspective of wood in rivers is itself a major knowledge gap. Most rigorous research on wood in rivers is accumulating at finer scales of spatial analysis, but understanding of full reach- and basin-scales and, especially, longer time scales is quite limited. These limitations form critical gaps in our knowledge of physical patterns and dynamics of wood in rivers and responses of ecological, geomorphic, and hydrologic processes to wood. In particular, current knowledge would benefit from a framework for developing more general conceptual models of wood dynamics and their effects.

Dealing with long-term dynamics of forest sources of wood and transport capacity of rivers is particularly challenging. Some changes in wood sources are progressive (for example, the loss of wood sources from streamside areas resulting from some types of land use) and others are abrupt (for example, loss of forest cover by major floods). Broad time and space perspectives are needed to sort out the trajectories of change in these systems and to reconstruct probable scenarios of past change. Natural and human-imposed disturbances in watersheds can affect sources, transport processes, and accumulation sites of wood. A whole-system view is required because interactions among components of the system and between natural processes and management practices are complex. For example, watershed disturbance can alter peak streamflow and potentially change the size distribution of wood pieces, thereby affecting wood transport. Channel modifications, including simplification by engineering practices, such as channelization, or, by simply removing large, jam-forming pieces, alter the wood retention and transport capacities of channels. Urbanization and agriculture over entire watersheds can impose whole-system change on wood dynamics by completely eliminating forests or severely limiting the extent and role of streamside forests. Intensive plantation forestry may reduce the height of streamside forests, possibly shifting upstream zones of wood influence on streams that are determined by the scale of tree height to stream width.

Understanding of effects of changes in wood in rivers is beginning to emerge for several components of river systems. Some observations suggest that greater pool complexity can permit more species and age classes of fish to occupy habitats, which could affect distributions more broadly in a watershed (Dolloff and Warren 2003, this volume). The amount of mobile wood in a river network may influence the distribution of riparian vegetation that colonizes after a flood, such as red alder *Alnus rubra* in Cascade Range streams in Oregon. Movement of wood in the 1964–1965 floods helped open riparian habitat for alder establishment, leading to expansion of this important nitrogen-fixing species. Geographic patterns and types of wood movement in third- to fifth-order channels during the 1996 flood in this area strongly influenced disturbance patterns of aquatic and riparian areas in the river network (Swanson et al. 1998; Johnson et al. 2000; Acker et al. 2003). The extent and arrangement of wood in a river system may also affect the cumulative influence of hyporheic zone processes, which can affect water temperature and chemistry (Grimm et al. 1991; Valett et al. 1996; Edwards 1998; Wondzell and Swanson 1999). Removal of wood from some river systems has been speculated to cause channel downcutting and reduction of water storage in channel bed and floodplain aquifers, thus potentially reducing flow during dry summer months and limiting rearing habitat for certain fish species (Montgomery et al. 2003, this volume).

A practical gap in knowledge of wood dynamics in rivers is how wood structures resulting from restoration projects or other management actions differ in form and function from natural wood structures. Profound differences between the managed and wild functions of wood in rivers may have long-term ecological and geomorphic consequences.

Framework for Further Work

A landscape perspective is fundamental to examining linkages over broad time and space scales in both natural and managed systems. Such a broad perspective is an essential context for study of the contemporary state of natural and managed systems. This perspective also provides a basis for determining how various management actions individually and collectively may alter the wood regime of the river system and whether this change is stepped or gradual. Restoration practices may be most effective when predicated on understanding of natural system dynamics.

Developing a framework for future research and management begins with existing relevant frameworks. One very useful framework is presented in this volume (Benda et al. 2003), which sets forth a mathematical approach to analysis of wood routing and budgets, including sources, transport processes, and accumulation sites, and the temporal dynamics of source forest stands and wood in river networks. A second relevant framework is the channel-morphology classification scheme of Montgomery and Buffington (1997, 1998), which emphasizes the interactions of bed steepness, lateral constraint, sediment supply, and transport capacity as they affect channel morphology at a series of spatial scales within watersheds.

The sediment routing system and channel

morphology classification considered in the scheme of Montgomery and Buffington (1997, 1998) and others differs from the wood routing system in several respects important to developing a conceptual model of wood dynamics in rivers and resulting patterns of wood. I hypothesize that wood pieces have much shorter mean transport distances in rivers than inorganic sediment because of the large size and irregular shapes of wood pieces and various factors favoring retention of wood in river systems (for example, burial and deposition in stable trapping sites). Also, decomposition of wood is more rapid than the rates of physical and chemical breakdown of most forms of inorganic sediment, so most wood leaves a river system as gas to the atmosphere or in solution, and as fine fragments transported downstream, rather than as large wood. Many rivers are floored with sediment and remain so through major flow events, which involve extensive turnover of the bed. Bedforms may change little through major transport events. Wood, on the other hand, generally covers a small fraction of a channel, and wood-affected channel forms are much more likely to be profoundly modified by input and transport events; thus wood configuration is likely to more strongly reflect recent events than do sediment bedforms. These factors of limited transport distances and residence time contribute to the patchy patterns of wood in rivers. Consequently, distributions of source areas, transport distances, and deposition sites are expected to have different implications for the arrangement of wood than for inorganic sediment. The wood routing system is more conducive to a patch dynamics and a landscape analysis approach than the physics/continuum thinking applied to sediment routing and bedforms.

A typology of wood dynamics that affect the arrangement of wood pieces in channels supplements the wood budget and sediment routing/bedform conceptual frameworks for rivers. This typology would consider the dominant controls on wood patterns by source area, transport, and deposition sites. Individual types of systems may cycle between expression of different types of control. Individual types of wood dynamics would be characterized in terms of the absolute and relative amounts of different types of wood accumulations, perhaps expressed as probability density functions for amounts of wood, as proposed by Benda and Dunne (1997a, 1997b). This information could then be used to examine long-term functions of wood in ecological and other respects of river reaches and networks of different type. This perspective of characterizing the range and change of conditions maintained under different systems could form a basis for examining effects of management practices and for designing restoration projects and other management actions.

How can we advance a comprehensive theoretical framework for wood dynamics in rivers? Current trends in research funding and the broad time and space scales required for this work may preclude establishing a single, widely accepted, integrated research effort to analyze wood dynamics across a diverse range of river and forest types. Therefore, a common conceptual framework of wood dynamics within which different research groups and agencies can accumulate relevant information would be useful in refining and testing the framework and advancing understanding. An important step in understanding wood in rivers is integration of the views of forest and river ecologists, hydrologists, geomorphologists, and others in a common analytical framework. Future research and management require combinations of retrospective, long-term monitoring, and modeling approaches to address a linked set of hypotheses about controls on wood patterns and dynamics.

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