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# Wood Recruitment Processes and Wood Budgeting

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*Abstract.*—Wood is recruited to rivers by a diversity of processes, including chronic mortality, windstorms, wildfires, bank erosion, landslides, and ice storms. Recruitment, storage, and transport of large wood in streams can be understood in terms of a mass balance, or quantitative wood budget, similar to the study of other material fluxes in watersheds. A wood budgeting framework is presented that includes numerical expressions for punctuated forest mortality by fire, chronic mortality and tree fall, bank erosion, mass wasting, decay, and stream transport. When used with appropriate parameter values derived for specific conditions or regions, the wood budget equations can be used to make predictions on the importance of various landscape processes on wood abundance in streams in any locale. For example, wood budgets can be used to predict how variations in climate (wet – dry), topography (steep – gentle), basin size (small – large), and land management could affect abundance and distribution of large wood in streams. Wood budgets also can be integrated into numerical simulation models for estimating the natural range of variability, specifically temporal fluctuations of wood supply driven by large storms, floods, fires, and mass wasting, and spatial variability driven by topographic heterogeneity and variations in wood transport. Field studies of wood in streams may be enhanced by the use of a wood budget framework. This includes specifying what measurements are required over what length of stream for estimating recruitment rates of all relevant inputs processes, wood loss by decay, and stream transport of wood. Finally, wood budgets can be used to estimate rates of bank erosion, forest mortality, and landsliding, given appropriate field measurements of wood in streams and riparian conditions.

# Introduction

More than 25 years of research have created a foundation for the development of a theory and quantitative framework for evaluating the mass balance, or budget, of large wood in rivers and streams. A wood budget is used to estimate the relative importance of different climatic, vegetative, and geomorphic processes on wood abundance in streams, including mortality, bank erosion, and landsliding across a range of spatial and temporal scales. In addition, wood budgets can also be used to predict the importance of instream wood supply from large regional disturbances, such as wildfires, floods, hurricane-force windstorms, and widespread mass wasting. This information could be helpful in quantifying the range of variability in wood supply and storage and to make predictions about how differences in landscape attributes (climate, topography, etc.) and land management lead to differences in instream wood abundance.

From a resource management perspective, interest in defining the necessary amount of instream wood is increasing. Most existing approaches and models consider input from mortality only (Bragg et al. 2000; Welty et al. 2002), and none of the current regulatory approaches considers recruitment from other processes (i.e., bank erosion, landsliding, etc.). Wood budgeting applied at the scale of whole watersheds can provide a useful tool for establishing realistic goals for wood management that consider spatial and temporal variability in recruitment processes. Fisheries biologists and foresters can apply that information to develop forest management prescriptions to ensure adequate wood supply to streams. Wood budgeting can also be used to estimate rates of forest mortality, bank erosion, and landsliding, information useful to foresters, ecologists, and geomorphologists.

In this chapter, the diversity of wood recruitment processes documented in the world's rivers is presented. To help understand the relative importance of different wood recruitment agents, we outline a new technology referred to as "wood budgeting." We begin with the quantitative framework for constructing wood budgets for any landscape in the world, addressing effects of fires, chronic tree mortality (suppression, disease, insects, and sporadic blowdown), bank erosion, and landsliding. Other less well-known processes, such as ice storms and ice-breakage in rivers, could be added to tailor the approach to different landscapes. Next, the numerical expressions are used to identify the data and field methods needed to estimate wood recruitment rates, source distance curves, wood transport, and other components of a wood budget. This is illustrated using data from several regions in the Pacific Northwest because, to the authors' knowledge, they represent the only studies conducted in the context of the wood budget methodology presented in this chapter. We also show how field data can be used to calculate rates of forest mortality and bank erosion. And lastly, we couple a wood budget to a landscape simulation model to predict the natural range of variability in wood abundance over centuries and to examine the role of rare and episodic processes.

Many studies have defined elements of wood budgets, and collectively they comprise the foundation for this chapter; only a partial list can be presented here. Keller and Swanson (1979) developed a conceptual wood budget for streams in the western Cascade Range by identifying the major inputs, outputs, and storage reservoirs. Likens and Bilby (1982) proposed a temporal relation among forest age, wood inputs, and the formation of wood jams in New England. Field measurements of in-channel wood in southeast Alaska by Murphy and Koski (1989) were used to define the relative contribution from stand mortality, bank erosion, and landsliding at the stream reach scale. From these data, they also estimated a wood depletion rate. Measurement of the diameters and lengths of wood in streams in the Oregon Cascades, southwest Washington, and southeast Alaska characterized the dimensions of pieces susceptible to fluvial transport (Lienkaemper and Swanson 1987; Bilby and Ward 1989; Martin and Benda 2001). Van Sickle and Gregory (1990) developed a wood recruitment model based on random tree fall. Field studies by McDade et al. (1990) and Robison and Beschta (1990) identified the source locations of recruited wood to streams. The importance of mass wasting on wood recruitment was identified by Swanson and Lienkaemper (1978), Everest and Meehan (1981), and Hogan et al. (1998). Recruitment of wood by hurricanes along coastal areas has been studied by Greenberg and McNab (1998). The importance of bank erosion as a tree recruitment agent in larger rivers was identified by Sedell and Froggatt (1984), Palik et al. (1998), and Piégay et al. (1999). Finally, simulation models have been developed to predict wood recruitment (Beechie et al. 2000; Bragg et al. 2000; USDA Forest Service 2002; Welty et al. 2002; Meleason, in press).

## Wood Recruitment Processes

We begin this chapter by reviewing the rich diversity of wood recruitment processes that have been documented worldwide. Much emphasis has been placed on wood recruitment by chronic mortality from the adjacent riparian forest, particularly in the Pacific Northwest region of North America. However, other processes of wood recruitment include hurricanes, floods, wildfires, bank erosion, landslides, and ice storms. Wood recruitment by different mechanisms reflects regional gradients of climatic, hydrologic, and geomorphic processes. For example, hurricane-force winds are more likely to occur near coastal areas, although massive blowdown has been documented in the middle of continents. Landslides that recruit large trees to streams are often concentrated in wet and steep coastal areas, such as along the Pacific Rim. Wood recruitment by bank erosion is more ubiquitous, although variation within watersheds occurs because bank erosion processes and rates vary downstream or, more locally, due to tributary confluences and other topographic knick points. Channel avulsion in floodplains is a major deliver source of wood in large rivers. Wildfires occur wherever large forests exist, perhaps with the exception of very humid coastal environments and tropical areas. This section briefly discusses each of the major wood recruitment processes in turn, describing some of the governing climatic and geomorphic conditions.

Forest mortality refers to a suite of tree killing processes, including blowdown (but distinguished from widespread, catastrophic blowdown; see below), insects, pathogens, and water logging; chronic mortality during early seral stages of forest growth is also referred to as "suppression mortality" or "stem exclusion" (Figure 1). Rates of forest mortality vary over time in any forest (Bormann and Likens 1979), and mortality

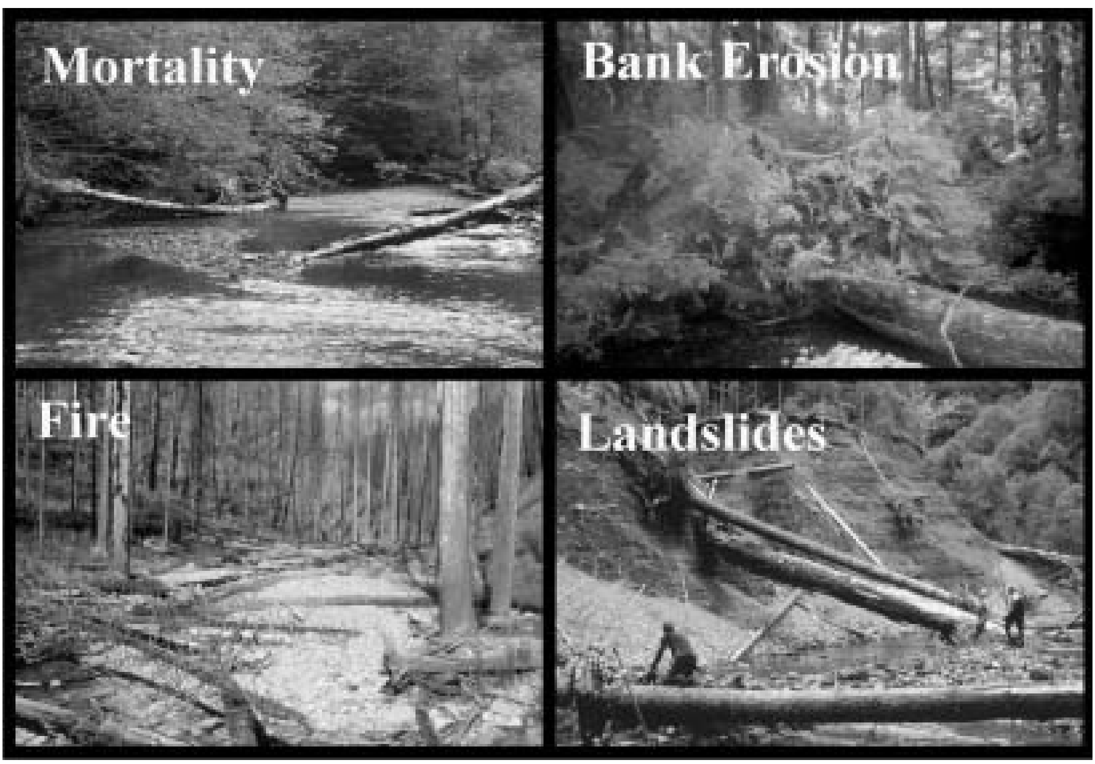



FIGURE 1. Wood recruitment to streams and rivers occurs by a diversity of processes. Shown here are forest mortality, bank erosion, landsliding, and postfire toppling.

rates also vary across regional climatic gradients (Benda et al. 2002). In early seral stages, instream wood is often associated with previous disturbances, such as fires, because wood recruitment in young forests is minimal (Hedman et al. 1996; Figure 1).

Catastrophic blowdown refers to widespread toppling of trees during a single event, such as during hurricanes (Greenberg and McNab 1998) or other downbursts (Wesley et al. 1998). As such, catastrophic blowdown occurs episodically, has recurrence interval of several centuries, and may dominate wood recruitment for decades.

Wildfires, particularly stand replacing events, can cause widespread tree death, including in riparian forests (Figure 1). Trees not killed outright by fire may later succumb to insect outbreaks or disease. In general, tree boles survive fire, although most branches, particularly the finer ones, can be consumed in the blaze (Agee 1993). Following fires, dead trees topple over after one to two decades, as their rooting systems decay or their weakened boles collapse in wind storms (Agee and Huff 1987). The importance of fires in tree recruitment depends on the frequency and severity of fires and their spatial extent, characteristics of fire regimes that vary over climatic gradients (Harmon et al. 1986; USDA Forest Service 2002; Benda and Sias 2003).

Bank erosion is an effective process that recruits trees to streams and rivers, in part because trees that are undercut tend to fall towards channels (Murphy and Koski 1989; Palik et al. 1998; Piégay et al. 1999; Martin and Benda 2001; Acker et al. 2003). Although bank erosion generally increases downstream (Hooke 1980), it also occurs nonuniformly and may even peak in areas associated with logjams, tributary confluences, and other fluvial topographic knick points (Figure 1). In large rivers, extensive sections of floodplains may be eroded during major floods, delivering large volumes of wood from floodplain forests (Piégay et al. 1999). Recruitment of wood to streams by bank erosion depends on the frequency and magnitude of floods, erodibility of stream banks, and the nature of streamside forests (Benda and Sias 2003). Bank erosion may not be differentiated from other recruitment processes in stand-level measures of chronic mortality in some studies.

Wood recruitment by landsliding is yet another important agent of wood recruitment, although its role in watershed-scale wood budgets is only recently being documented (Hogan et al. 1998; Benda et al. 2002; Reeves et al. 2003). Wood recruitment occurs by a diversity of mass wasting processes, including small, streamside landslides and larger, deep-seated failures that transfer wood from hill slopes to channels (Figure 1). In contrast, debris flows scour the long-accumulated wood in first- and second-order channels and deposit jams downstream in larger, often fish-bearing streams. Although debris flows fall into the domain of mass wasting, they are considered primarily an agent of wood redistribution at the channel network scale. Conditions necessary for wood recruitment by mass wasting includes steep slopes, narrow valley floors, and intense precipitation. Therefore, streams and rivers in mountain regions are more likely to have significant contributions of wood from mass wasting.

There are a number of less well known wood recruitment processes that may be regionally important. Ice storms that can kill trees outright, although, in many cases, ice coating, combined with wind, is more effective at breaking off limbs. Ice storms have increased wood loading to first- through third-order channels in the northeastern United States and Canada (Kraft et al. 2002). Another process that may be locally important is ice break and rafting in rivers. Ice dams may form in rivers during spring thaws, and floating ice can scour riverbanks, creating a form of bank erosion. Yet another process is dam-break floods. Landslide dams that breach often send a flood wave downstream that can be highly erosive and scour streambanks (Costa 1988).

The diversity of wood recruitment processes presents a challenge to researchers, resource managers, and regulators. Most studies of instream wood have not differentiated among various wood recruitment agents. Nevertheless, it is increasingly necessary to evaluate the relative importance of different recruitment processes, in particular how they vary across watersheds or regions. This information can be used to help design wood recruitment strategies (for example, riparian buffer strips), to understand the role of rare and episodic processes on long-term wood recruitment (such as fires, windstorms, landslides), and to begin to understand natural variability of recruitment that may have consequences for designing river restoration and monitoring programs. The theory, technology, and modeling of wood budgeting, presented in the remaining parts of the chapter, can help address the challenge of understanding the relative importance of the diversity of wood recruitment processes worldwide.

## Quantitative Framework

### Mass budget

Environmental systems with definable inputs, outputs, and residence or storage times lend themselves to an accounting of material fluxes over time and space in the form of a mass balance or budget. Techniques for evaluating mass budgets for other watershed processes have been developed, including erosion and sediment supply (Dietrich and Dunne 1978; Reid and Dunne 1996) and the hydrologic cycle (Dunne and Leopold 1978). Similarly, a wood budget is concerned with the differences among input, output, and decay of wood, a relationship that can be expressed as

$$\Delta S = I\,\Delta x - L\,\Delta x + (Q_i - Q_o) - D\,\Delta t\,, \quad (1)$$

where $\Delta S$ is a change in wood storage in a reach of some length $\Delta x$ over the time interval $\Delta t$ (Benda and Sias 2003). Change in wood storage is a consequence of wood recruitment ($I$), loss of wood from over-bank deposition in floods and abandonment of jams ($L$), fluvial transport of wood into ($Q_i$) and out of ($Q_o$) the segment, and in situ decay ($D$). The terms $I$ and $L$ have units of volume per unit reach-length per time, and the remaining terms ($Q_i$, $Q_o$, and $D$) have units of volume per time (Table 1). The values of these terms will vary depending on position in the channel network. Figures 2A and 3 provide a flowchart and a schematic illustrating the components of a wood budget.

Wood is delivered to channels from a variety of sources. Total input can be summarized as

$$I = I_m + I_f + I_{\mathrm{be}} + I_s + I_e\,. \quad (2)$$

Inputs include tree mortality from disease, suppression, and sporadic blowdown ($I_m$); toppling of trees after stand-replacing fires and during windstorms ($I_f$); inputs from flood-induced bank erosion ($I_{\mathrm{be}}$); wood delivered by landslides, debris flows, and snow avalanches ($I_s$); and exhumation of wood buried in the bed or bank or recapture of wood previously deposited on the banks ($I_e$). Mortality refers to the death and toppling of trees, and, though these processes may be offset in time, they are represented by a single rate (that is, long-term chronic mortality is equivalent to long-term toppling). Other processes could be added as needed, for example, ice breakage in rivers.

### Forest mortality and growth

Wood delivery to streams from forest death can be viewed as the product of either chronic input of relatively small volumes of wood or rare, episodic events that can add massive quantities of wood over a short time (hours to years). Chronic inputs are caused by competition-induced suppression, insects, and disease. Episodic inputs of large quantities of wood can include wildfires (Agee 1993) and windstorms, processes that often cause widespread tree death and initiation of new forests. Blowdown is also an important process in managed forests (Grizzel and Wolff 1998).

The rate of recruitment from chronic mortality ($I_m$ in equation (2)) can be expressed as

$$I_m = B_L * M * H * P_m * N\,, \quad (3)$$

where $I_m$ is the average flux of wood per unit channel length per unit time; $B_L$ is volume of standing live and dead trees per unit area; $M$ is the rate of forest mortality; $H$ is average stand height; $P_m$ [dimensionless] refers to the stand-average fraction of stem volume or length that becomes in-channel wood when trees fall by mortality; and $N$ is 1 or 2, depending on whether one or both sides of the channel are forested (Table 1; Benda and Sias 2003). The term $P_m$ is described later in the chapter. All parameters are functions of time and position, and over any given channel length and time, all exhibit a distribution of values that may be characterized by a mean and some measure of variability. For simplicity, the effect of time is not explicitly included in equation (3) or in subsequent equations in this chapter, and steady state assumptions may be acceptable over short periods (years to a few decades) for most field studies. Over longer periods, however, the effect of time and stochastic processes on the parameters of all the mass balance equations may need to be considered.

The recruitment of fire- or wind-derived wood ($I_f$ in equation (2)) is calculated similarly:

$$I_f = B_f * T_f * H_f * P_m * N\,, \quad (4)$$

where $I_f$ is the average annual flux of fire- or wind-killed trees ($I_f$ is zero during all other times), $B_f$ is the volume of standing trees just prior to the fire or windstorm, $T_f$ is the annual proportion of the volume toppled during a specific period during or after the event, and $H_f$ is the average height of trees (Table 1). The frequency of fires or wind-

TABLE 1. Notation, variable descriptions, and variable dimensions in wood budgeting.

| Notation | Variable description | Dimensions | Notation | Variable description | Dimensions |
|---|---|---|---|---|---|
| $\Delta S$ | Wood storage | $m^3$ | $T_f$ | Toppling period | year |
| $I$ | Wood input | $m^3\ m^{-1}\ year^{-1}$ | $E$ | Bank erosion | m / year |
| $x$ | Measurement length | m | $P_{be}$ | Probability of tree fall (bank erosion) | % |
| $L$ | Wood loss | $m^3\ m^{-1}\ year^{-1}$ | $S_s$ | Wood storage in landslide zone | $m^3 / m^2$ |
| $Q_i$ , $Q_o$ | Wood transport | $m^3$ / year | $A_s$ | Landslide area | $m^2$ |
| $D$ | Decay | $m^3$ / year | $N_s$ | Number of landslide per channel length | # / m |
| $I_m$ | Mortality recruitment | $m^3\ m^{-1}\ year^{-1}$ | $T_s$ | Frequency of landslides | per year |
| $I_f$ | Fire recruitment | $m^3\ m^{-1}\ year^{-1}$ | $R_c$ | Landslide delivery ratio | % |
| $I_s$ | Landslide recruitment | $m^3\ m^{-1}\ year^{-1}$ | $k_d$ | Decay constant | # / year |
| $I_e$ | Exhumation recruitment | $m^3\ m^{-1}\ year^{-1}$ | $\phi$ | Proportion of mobile pieces | % |
| $I_{be}$ | Bank erosion recruitment | $m^3\ m^{-1}\ year^{-1}$ | $\zeta$ | Lifetime travel distance | M |
| $B$ | Forest volume per unit area | $m^3 / m^2$ | $L_j$ | Interjam distance | M |
| $M$ | Mortality rate | % / year | $T_p$ | Lifetime of wood | year |
| $H$ | Tree height | m | $T_j$ | Lifetime of jam | year |
| $P_m$ | Probability of tree fall (mortality) | % | $L_p$ | Piece length | m |
| $N$ | Number of banks | # | $\beta$ | $L_p$ / channel width | % |

storms will govern the relative importance of episodic tree recruitment processes compared to chronic forms of mortality.

## *Stream bank erosion*

Rates of tree recruitment from bank erosion during floods depend on erodibility of banks, flow energy, flood frequency and magnitude, and stand density. The resistance of stream banks to erosion is influenced by composition of the bank material and reinforcement by roots (Hooke 1980). Bank erosion is often greatest in lower, actively migrating portions of channel networks, although it may also peak in the mid-regions of river networks (O'Connor et al., in press). Banks also erode when flow is diverted around debris jams and other obstructions. An expression for mean wood recruitment from bank erosion depends on standing forest volume, rate of bank retreat, and the fraction of tree length that can intersect a channel, or

$$I_{be} = B_L * E * P_{be} * N , \qquad (5)$$

where $I_{be}$ is annual wood supply to streams, $E$ is mean bank erosion rate (lateral distance eroded per year), and $P_{be}$ is the fraction of stem length of fallen trees that is deposited into the channel ($0 < P_{be} \leq 1.0$) (Benda and Sias 2003). $P_{be}$ is analogous to $P_m$ in equations (3) and (4) but generally has a larger value, since all trees recruited by bank erosion are immediately adjacent to the channel, and trees undercut by bank erosion tend to fall toward the channel (Murphy and Koski 1989). Equation (6) predicts annual wood recruitment for a given value of $B_L$ and could be used to predict episodic wood influx by treating $E$ as a stochastic variable.

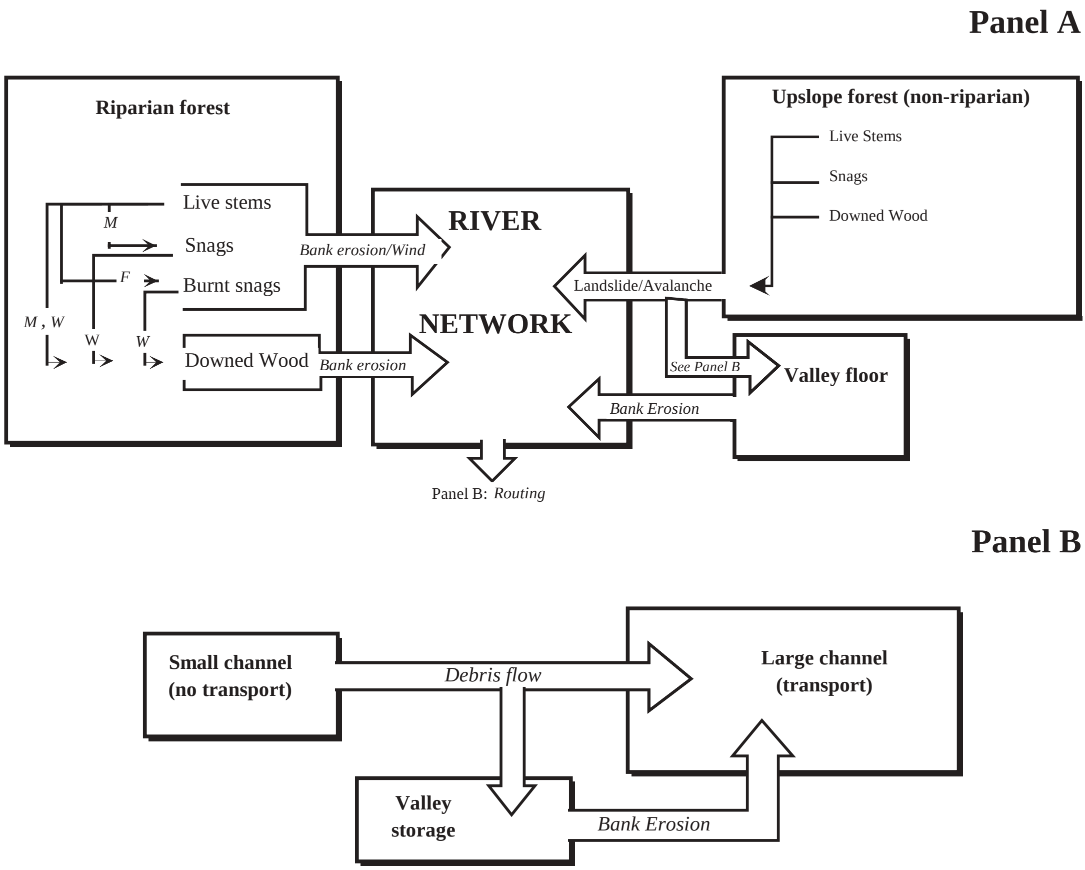



FIGURE 2. Flowchart indicating the major components of a wood budget (from Benda and Sias 2003). Panel A: Fire (F), wind (W), and mortality (M) transfer woody debris to streams and forest floors. In riparian forests, wind and bank erosion transfers wood to rivers. Landslides and snow avalanches recruit live and dead trees to streams, a portion of which may be deposited on valley floors. Panel B: fluvial transport, including debris flows in small, headwater channels.

## *Mass wasting and snow avalanches*

Shallow and deep-seated landslides, debris flows, and snow avalanches recruit wood to channels and valley floors (Swanson and Lienkaemper 1978; Fetherston et al. 1995; Hogan et al. 1998). The importance of wood recruitment by mass wasting depends on the type and area of the landslide or debris flow, sizes of trees recruited, number of landslide or debris flow source areas intersecting a channel segment of a given length, temporal frequency of landsliding or debris flows, and fraction of wood entrained by the event. Landslides and avalanches may deposit partially on fans and terraces at the base of hill slopes, thereby reducing the amount of wood delivered to a channel. The influx of wood from landslides, therefore, can be expressed as

$$I_s = S_s * A_s * N_s * T_s^{-1} * R_c , \qquad (6)$$

where $I_s$ is the wood recruitment by mass wasting or by avalanche; $S_s$ is the storage of live and dead wood in the areas entrained; $A_s$ is landslide, debris flow, or avalanche path area; $N_s$ is the number of landslide sites or debris flow tributaries that intersect the downstream (receiving) channel (number per channel length); $T_s$ is the average landslide or debris flow recurrence interval (i.e., 1/year); and $R_c$ is the delivery ratio (the proportion of trees that enter the channel) (Table 1). Although equation (7) predicts an average annual flux, mass wasting and avalanches occur as stochastic events, and the episodic nature of wood recruitment by mass wasting can be simulated by stochastic models (see below).

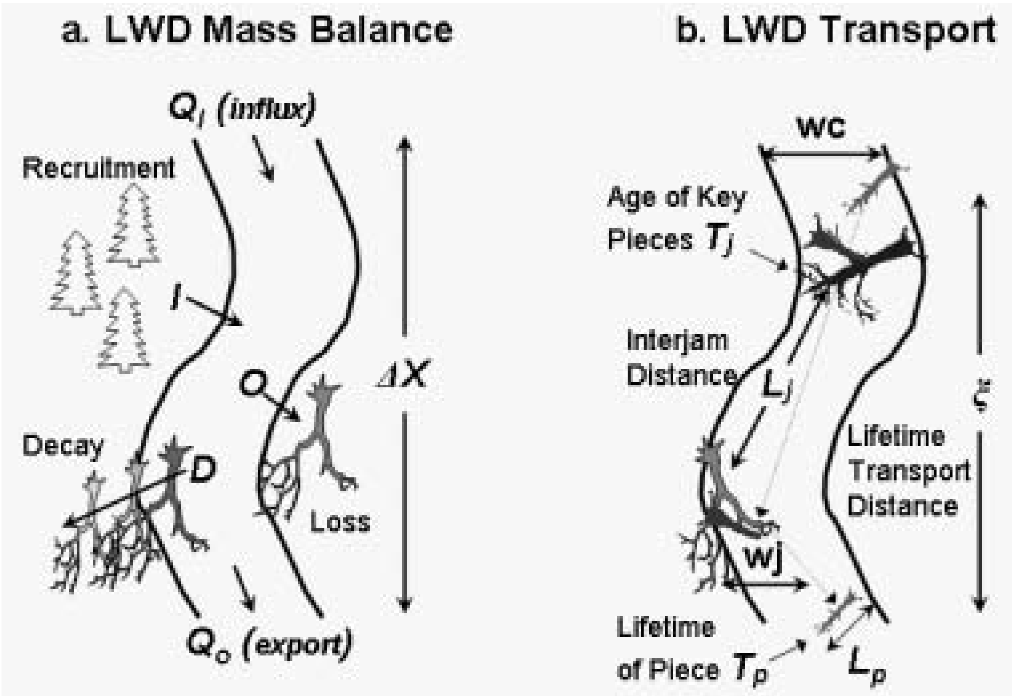



FIGURE 3. (a) A schematic illustrating the major inputs and outputs of a wood budget, including parameters for wood transport (b) (from Martin and Benda 2001).

## *Wood decay*

Wood decay (*D* in equation (1)) limits the longevity of wood that falls on forest floors or into streams, and it is governed by numerous physical and biological factors. Field studies have shown that annual decay of conifer wood in forest-floor environments commonly ranges from 2% to 7% per year (Harmon et al. 1986; Spies et al. 1988). Streams also exert hydraulic forces that abrade wood or breakup decayed and mechanically weakened wood into smaller transportable pieces. Estimates of annual decay rates for submerged wood ranged from 2% to 3% per year, depending on tree species found in the Pacific Northwest region of North America (Bilby et al. 1999). Estimates of wood loss in unmanaged streams (including decay, abrasion, and transport) have ranged between 1%/year in southeast Alaska (Murphy and Koski 1989) and 3%/year in the Olympic Peninsula (Hyatt and Naiman 2001).

Decay can be expressed as an exponential process:

$$D(x,t) = k_d \ S \ , \tag{7}$$

where $k_d$ is decay loss per unit time and *S* is storage volume (Harmon et al. 1986). Integrating equation (7) with time yields an exponential loss of wood volume. Wood decays primarily in equation (7) due to a loss of mass (i.e., decreasing wood density) (Hartley 1958). Loss of mass, however, should equate with loss of strength and, therefore, wood decay in fluvial environments is assumed to occur by breakup of wood into very small pieces that cannot be effectively captured by jams (or other obstructions) and that exit the system as floatable wood pieces. Transport of wood is covered below, and abrasion of wood during transport is not included.

## *Stream transport of wood*

Understanding how wood moves in a channel network may be an important component of a wood budget. For example, wood transport can alter the distribution of wood, increase jam size, and export wood to estuaries and marine environments. Wood transport may also be of interest when managing the supply of wood to streams (Martin and Benda 2001). Field studies have shown that wood transport depends on several factors. Transported pieces tend to be shorter than bank-full width because larger pieces become lodged between banks (Lienkaemper and Swanson 1987; Nakamura and Swanson 1993; Martin and Benda 2001). In addition, transport distances are limited by obstructions such as debris jams (Likens and Bilby 1982). Hence, because channel width generally increases downstream, an increasing proportion of all wood becomes mobile if the distribution of recruited piece sizes remains constant (Bilby and Ward 1989; Martin and Benda 2001). Wood transport is also affected by stream power (slope and stream cross-sectional area) and flow depth (Haga et al. 2002). Other complexities include the diameter of logs (Bilby and Ward 1989), piece orientation and the presence of root boles (Abbe and Montgomery 1996; Braudrick and Grant 2000), and wood density (Piégay and Gurnell 1997).

Here, we present a wood-transport equation based on the following assumptions. First, wood transport is dependent on the proportion of pieces that are mobile, defined as pieces shorter than channel width at bank-full stage. Second, the transport distance of wood during the lifetime of a piece is dependent upon the lifetime of wood, the distance between transport-impeding jams, the longevity of jams, and the proportion of channel width spanned by jams. The transport equations are more suitable for examining large-scale patterns of wood redistribution and the jam frequencies and sizes that would arise throughout watersheds over decades. They are less suitable for predicting wood movement at the reach scale over a few years because of the complexities that were omitted. Fluvial transport of wood is defined here as

$$Q_w = I \phi \xi \ , \tag{8}$$

where $Q_w$ is the volumetric wood transport or flux rate at a cross section (equivalent to $Q_i$ or $Q_o$ in equation (1), $I$ is the average volumetric rate of lateral recruitment, $\phi$ is the long-term average proportion of all recruited wood with piece lengths ($L_p$) less than the channel width, and $\xi$ is transport distance over the lifetime of a piece (Benda and Sias 2003). In equation (8) the relative proportions of mobile to nonmobile wood remain constant over time (although they may vary spatially in a network) because of continuous tree recruitment (this assumption may not hold during episodes of very high or very low recruitment). The transport distance ($\xi$) over the lifetime of wood is predicted by

$$\xi = L_j(T_p / T_j)\beta^{-1} \quad \text{for} \ T_p >= T_j \ , \tag{9}$$

where $L_j$ is the average distance between transport-impeding obstructions, $T_p$ is the lifetime of wood in fluvial environments, $T_j$ is jam longevity, and b is the proportion of channel spanned by a jam (Figure 3b). Equation (9) expresses a hypothesis that transport of wood can exceed inter-jam spacing when wood longevity exceeds jam longevity, and/or when less than 100% of jams are channel-spanning ($\beta < 1.0$). Location and time indices are omitted in equation (9), although our expectation is that all dependent variables (and therefore also the independent variable $\xi$) will be a function of network position and of time. The main influence of time is stand-age dependence of size and longevity of jam-forming pieces and mobile wood.

Given that $\beta$ cannot exceed unity, the constraint $T_p = T_j$ ensures that $\xi$ cannot be less than $L_j$. This fulfills an assumption that wood travel time from location of recruitment to the next downstream jam is much shorter than jam longevity (i.e., mobile wood is quickly transported downstream until its migration is impeded by a partial and channel-spanning jam). Accordingly, wood will tend to accumulate at jams, rather than being distributed along channel margins throughout the inter-jam space. This model does not require any consideration of flood frequency and how it changes, for example, with drainage area and climate.

Equations (8) and (9) apply only to streams and rivers where transport is limited by jams; they do not address transport in larger rivers with other forms of wood storage, such as on floodplain and in off-channel areas.

## *Estimating the proportion of wood falling into streams*

The stand-average proportion of wood volume or length that becomes in-channel pieces from all trees in a streamside forest is referred to as $P_m$ and $P_{be}$ in equations (3)–(5). These dimensionless parameters take into account variable fall angle (not all trees will fall directly toward the channel) and variable source distance (any stem within a distance $H$ from the streambank has the potential to contribute wood to the channel). Van Sickle and Gregory's (1990) geometric fall model is used to calculate $P_m$ for all possible combinations of source distances and fall angles (piece breakage can also be incorporated, see Benda and Sias 2003; Sobota 2003). $P_{be}$ is estimated in the same manner as $P_m$, except that source distance is limited to one meter and trees are constrained to falling within an 180° arc circumscribed by the adjacent bank. Further, our calculation of $P$ assumes that trees are cylinders to avoid the complexity of how the bole's taper varies with species, height, and tree age; taper could be added to the estimation of $P$ when information is available. At any specific time, the random nature of tree fall will cause the value of $P$, appropriate for a given reach, to fall within some range of values. For any given channel reach, $P$ will vary according to mean tree height (or taper), distance of trees from a channel, and channel width (Figure 4). P is independent of tree mortality rates and simply reflects the cumulative proportion of all tree lengths in a riparian forest that would intersect a stream.

Using this approach, average $P_m$ is about 0.10 for a 15-m-wide channel and an average 50-m tree height (that is, 10% of the cumulative length of all trees intersect the channel and becomes instream wood; Figure 4A). In contrast, $P_m$ is 0.05 in 5-m-wide channels with the same tree height. The term $P_{be}$ values for bank erosion are significantly higher, assuming a 100% fall probability towards the channel when trees are undercut (Figure 4B). $P$-values decrease dramatically with distance from stream, and higher values are associated with smaller tree heights (Figure 4C). Field measurements should be used to define $P$ in terrains where random fall assumption may not apply or where studies occur over relatively short reach lengths. A recent study in Oregon, Washington, Idaho, and Montana found that tree fall angle was significantly directional toward the stream channel and variance in tree fall angle decreased with increasing hill slope gradient (Sobota 2003).

## Field Methods

The quantitative framework provided by wood dynamics models, as illustrated in equations (1)–(9), dictates the type of field measurements necessary to define a wood budget (Figures 2 and 3). In general, wood storage should be tabulated in terms of volume, rather than pieces, because pieces do not discriminate between very small and very large wood. However, wood storage defined as pieces may have more ecological significance. Constructing a field-based wood budget requires making quantitative estimates of wood recruitment (volume / length / time) by fires, chronic mortality, bank erosion, landsliding, and snow avalanches. Field based wood budgets will also require determining the time of fall of individual trees; (Murphy and Koski 1989; Hyatt and Naiman 2001; Martin and Benda 2001; Benda et al. 2002). In general, trees and shrubs that originate by the falling tree (i.e., either dependent samplings growing on boles or rootwads or vegetation established by disruption of pre-existing groundcover) is used to date timing of tree falls.

The time over which pieces of wood are recruited to streams can be estimated by

$$\Delta T = \left(\sum_{i=1}^{n} a_i p_i\right) , \qquad (10)$$

where $a_i$ is the mean age of wood in decay class $I$, and $p_i$ is the proportion of wood in decay class $i$ in any segment (Harmon et al. 1986; Murphy and Koski 1989; Hennon et al. in press); The term $\Delta T$ over short time periods is sensitive to the sequence of recruited trees of various sizes (i.e., $\Delta T$ would be significantly different if a large tree fell in year 10 versus year 1 during a 10-year period). Hence, the proportion of wood in each decay class is based on number of trees, rather than on volume, to reduce the variability in ΔT that can arise due to variation in the temporal sequence of recruitment. In addition, equation (10) gives more weight to trees that have been recruited longer ago to account for the assumed increasing loss of trees (and hence their undercount) with increasing time since recruitment (Murphy and Koski 1989).

Other pertinent field measurements may include forest age, forest volume per unit area, tree height, wood decay, jam spacing and size, jam longevity (age), and wood storage on floodplains, terraces, and fans. Measurements of other watershed attributes may also be necessary, including landslide history and slide-prone topography. Although full wood budgets may be useful for certain purposes, individual components of a wood budget may focus more narrowly on certain aspects, including defining recruitment processes, size distribution of organic debris, source distances, and wood transport. Data required for these more focused questions may not be as extensive as those needed for a complete wood budget.

### *Determining length of study reaches*

Those developing wood budgets are confronted with two important sampling questions: how long

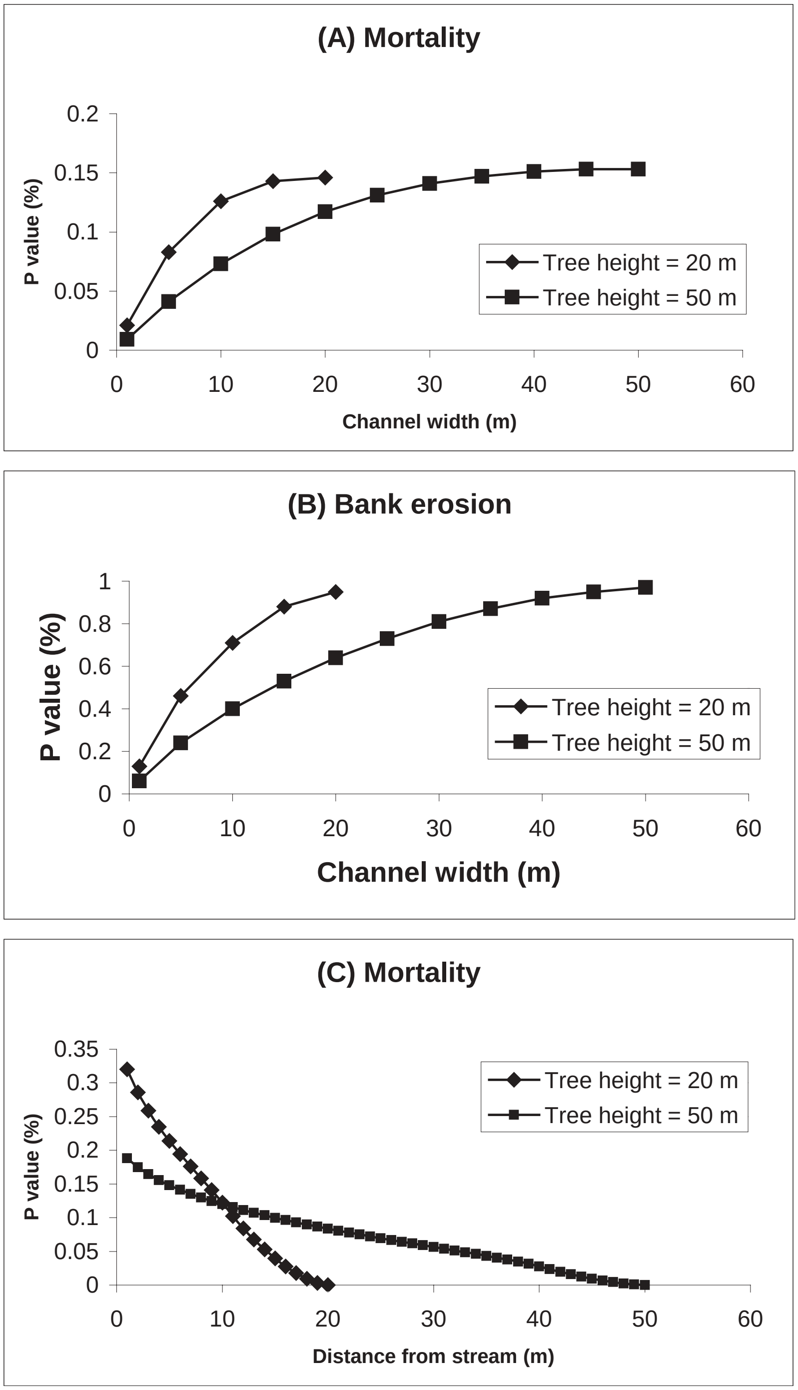



FIGURE 4. (A) Stand average proportion of forest biomass that becomes instream wood depending on tree height and channel width (assumes random fall over 360°). (B) Stand average proportion of forest biomass that becomes instream wood due to bank erosion according the tree height and channel width (assumes 100% fall probability within a streamside 180° arc that intersects the channel). (C) Stand average proportion of forest biomass that becomes instream wood according to distance away from channel edge for two different tree heights (10-m-wide channel).

should study reaches be, and over what periods should studies be conducted? Generally, instream wood is measured in a single year, but in some rare instances, studies have repeatedly measured wood at a site to determine wood longevity or transport rate (e.g., Gregory et al. 2000). Although the duration of studies may be restricted, generally more flexibility exists in designating the length of sample reaches. To obtain a good estimate of the relative importance of different recruitment processes, the length of the study reach will depend on the rate at which wood is recruited (and possibly the rate at which wood is lost). A short study reach (~hundreds of meters) may be acceptable in areas of high recruitment, but a longer reach may be necessary in regions of low wood recruitment to accurately characterize input rates. Another confounding aspect is the stochastic behavior of wood recruitment, in which a single large storm, flood, or fire delivers (or removes) large volumes of wood in streams.

The wood recruitment equations in this chapter can be used to estimate lengths of study reaches that might be suitable. To illustrate, we estimate the reach length necessary to measure wood recruitment in areas of different bank erosion rates (a similar technique can be applied to mortality or landslides). The analysis assumes a constant rate of tree recruitment; more sophisticated analyses (such as Monte Carlo simulation) could incorporate the stochastic nature of bank erosion and of other recruitment processes. Bank erosion rates can frequently range from 0.01 m / year to more than 1 m / year (Hooke 1980). To estimate a survey distance, first define the amount of wood to measure (that amount accumulating over a particular time). In this example, our target is a minimum of three trees that entered a channel over a period of 10 years. Begin by estimating the volume of in-channel wood contained in three trees in a 10-m-wide channel. If an average diameter of 1 m is used, the required volume to measure is about 94 $m^3$ (applying the geometry of a cylinder). Next, the standing forest volume is estimated; here, we use a $B_L$ of 0.25 $m^3/m^2$. We can ignore $P$ because measured instream wood already accounts for the proportion of wood intersecting a channel. Solving for distance in equation (5) requires a survey of about 3 km of stream to measure three trees with a bank erosion rate of 0.01 m / year (for both sides of the stream) and a survey of 0.03 km for an erosion rate of 1 m / year. Temporal variability in mortality rates and in $P$ will cause variation in the amount of wood actually encountered along 6 km of stream, and survey distances may be longer or shorter than those predicted.

## Estimating sources and rates of wood recruitment

Most wood studies have not estimated recruitment rates, partly because of the absence of a wood-budgeting technology. We present results from two recent studies that have estimated recruitment rates: southeast Alaska (Martin and Benda 2001) and redwood forests of northern California (Benda et al. 2002). Game Creek (132 $km^2$), on Chichagof Island in southeast Alaska, is forested by old-growth western hemlock *Tsuga heterophylla* and Sitka spruce *Picea sitchensis*. The study sites in old-growth redwoods *Sequoia sempervirens* are located in Redwood State Park (Prairie Creek, 57 $km^2$), northern California. The southeast Alaska and northern California wood budgets estimated recruitment rates for chronic mortality, bank erosion, and landsliding over 40 years and 20 years, respectively (reflecting the time over which wood entered channels. e.g., equation (10)).

Both wood budget studies revealed a high degree of spatial variability driven by stream differences in recruitment processes and wood transport. For example, in Prairie Creek, instream wood volumes varied by a factor of 30 (maximum) at the scale of 100-m reaches (Figure 5). Some of the variability is linked directly to variation in recruitment processes.

To estimate recruitment rates over relatively short periods (<2 decades), we can omit stream transport (that is, $Q_i$ and $Q_o$ are assumed be equivalent), loss of wood from over-bank deposition in floods and abandonment of jams ($L$), and in situ decay ($D$).

Consequently, equation (1) reduces to

$$\Delta S / (\Delta T \Delta X) = (I_m + I_{be} + I_s) \ , \qquad (11)$$

where ΔS is the change in recruited wood storage ($m^3/m$), $\Delta X$ is length of study segments over some elapsed time period ΔT (i.e., equation (10)). The estimated recruitment rate is high in second-growth redwoods compared to old-growth redwoods (4 versus 2.5 $m^3$ / km / year; Figure 6), a difference driven by a low mortality rate in old growth (see below).

In both regions, recruitment from bank erosion, landsliding, or both dominated the wood

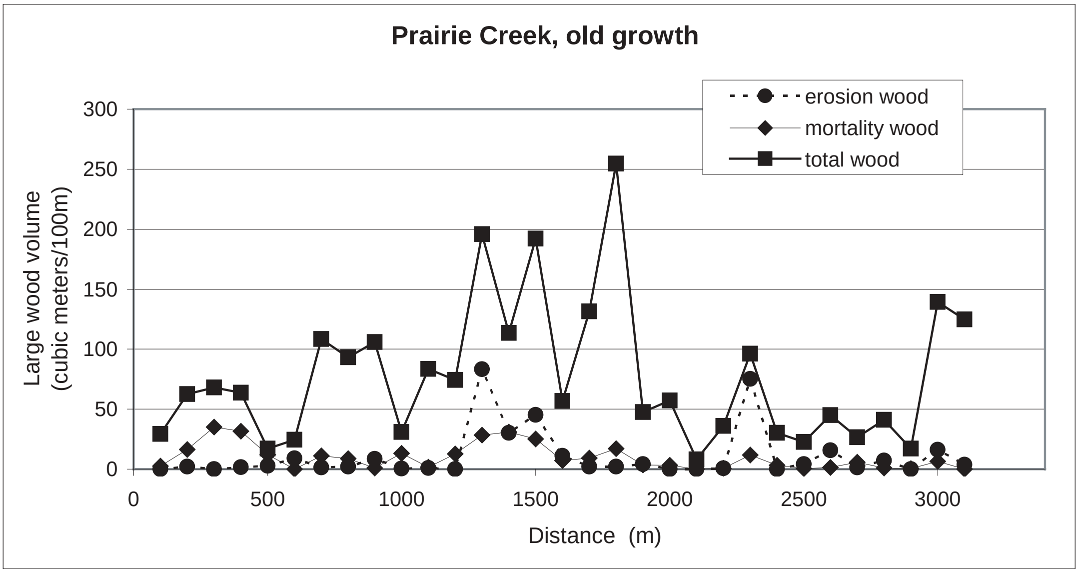



FIGURE 5. Wood storage and recruitment processes in old-growth redwood forests reveal a high degree of spatial variability.

budget (Figure 6). The southeast Alaska budget exhibited a trend of increasing bank-recruited wood with increasing drainage area (Martin and Benda 2001), a finding consistent with increasing bank erosion with increasing basin size. Theoretically, a crossover point in a channel network should be reached where bank erosion recruitment exceeds mortality recruitment (estimated at a bank erosion rate of 0.05 m / year (one side of channel) in mature Douglas-fir forests if an average mortality rate of 0.5% / year is used (Benda and Sias 2003). In the Game Creek watershed, the average mortality recruitment rate of about 4 $m^3$ / km / year (corresponding to an average mortality rate of 1.5% / year) was exceeded by bank erosion recruitment at a drainage area of about 20 $km^2$ (equivalent to a bank erosion rate of 0.07 m / year).

## Estimating source-distance curves

Defining the distances to wood sources in a riparian zone is important in designing forest management and applying regulatory policies. The proportion of wood (either in length or volume) that enters a channel declines with increasing distance from the channel edge. This relation has been demonstrated both empirically and through model simulations (McDade et al. 1990; Robison and Beschta 1990; Meleason et al., in press). The cumulative distribution plot that indicates how the proportion of wood input declines with distance from the channel is referred to as a "source-distance curve." The source-distance curve of wood volume (or length) is sensitive to both tree height and channel width. The proportion of wood volume decreases continuously with distance from a stream because a decreasing proportion of random-fall trajectories intersect the channel (e.g., Figure 4C), and the diameter of the bole decreases. To estimate source distance curves during field studies, the distance from the channel edge to the source of wood is measured for each piece where the source can be determined.

Source distance curves are sensitive to different recruitment processes. A theoretical prediction of the source distance curve for mortality recruitment only (assuming a 360° random fall probability) for two different tree heights in a 10-m-wide channel is shown in Figure 7. For comparison, two empirically derived source-distance curves are also plotted, but they include bank erosion and landsliding, recruitment processes that cause a greater proportion of wood to enter closer to the channel. Landslides entering streams not initiated in the streamside zone, especially those that propagate as debris flows, can cause a greater proportion of wood to enter channels from distances further away (May 2001).

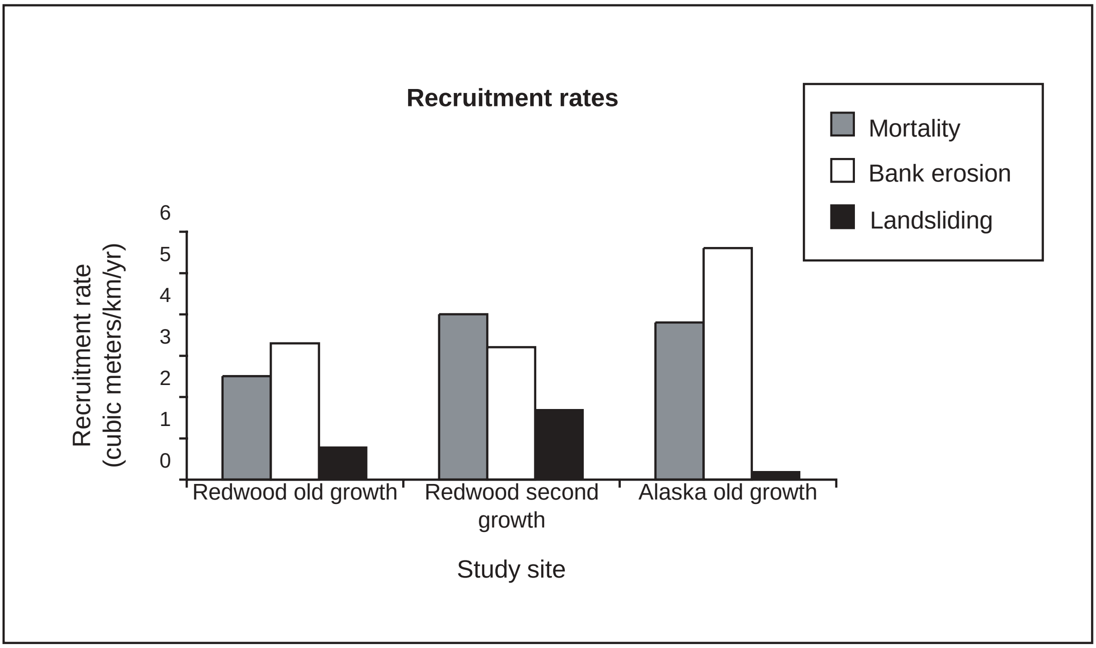



FIGURE 6. Nonmortality sources dominate wood recruitment rates in unmanaged forests in southeast Alaska and in northern California.

## *Estimating wood recruitment from mass wasting*

Numerous field studies have observed that landslides and debris flows deliver large amounts of wood to streams in the Pacific Northwest ecoregion (Swanson and Lienkaemper 1978; Murphy and Koski 1989; Hogan et al. 1998; May 2001). Our experience in the Pacific Northwest indicates that wood delivered to streams by landslides can be measured in two ways. The first method requires conducting long, continuous surveys (~kilometers) to identify the number of pieces of wood recruited by mass wasting. Either the proximity of pieces to landslide debris or the piece condition (landslides and debris flows often leave large scars) can often be used for identification. The second method, which does not require associating pieces with recruitment, evaluates all wood as to distance from mass-wasting source areas, such as debris flow deposits at headwater tributary junctions. This second method is a statistical analysis of relationships between wood accumulations and potential sources of mass wasting and identifies potential delivery from mass wasting rather than actual delivery. Both types of survey procedures are plotted in Figure 8.

Mass wasting, particularly debris flows, may create a clumped distribution of wood in both unmanaged and managed basins (Figure 8). Between debris-flow deposits in our field example in an unmanaged basin in the Oregon Coast Range (Figure 8A), little wood is found, in part because of low forest mortality (in 150-year stands) and the prevalence of small deciduous trees in riparian forests (Nierenberg and Hibbs 2000). In the Oregon Coast Range study, mass wasting was responsible for 80% of instream wood. In second-growth forests in the Olympic Peninsula, Washington, there was a statistically significant correlation ($p$ = 0.1) between in-channel wood storage (across 6 km of third- and fourth-order channels) and proximity to debris flow deposits at low-order confluences; the largest volumes of wood were located 25–50 m from low-order confluences (Benda et al., in press; Figure 8B). Other studies in the Coast Range have observed that approximately half of the wood was derived from mass wasting (May 2001; Reeves et al. 2003). The concentration of wood, and also boulders from debris flows, may lead to clumping or wave-like distribution of aquatic habitat features (Everest and Meehan 1981; Reeves et al. 1995; Benda 1990; Benda et al., in press).

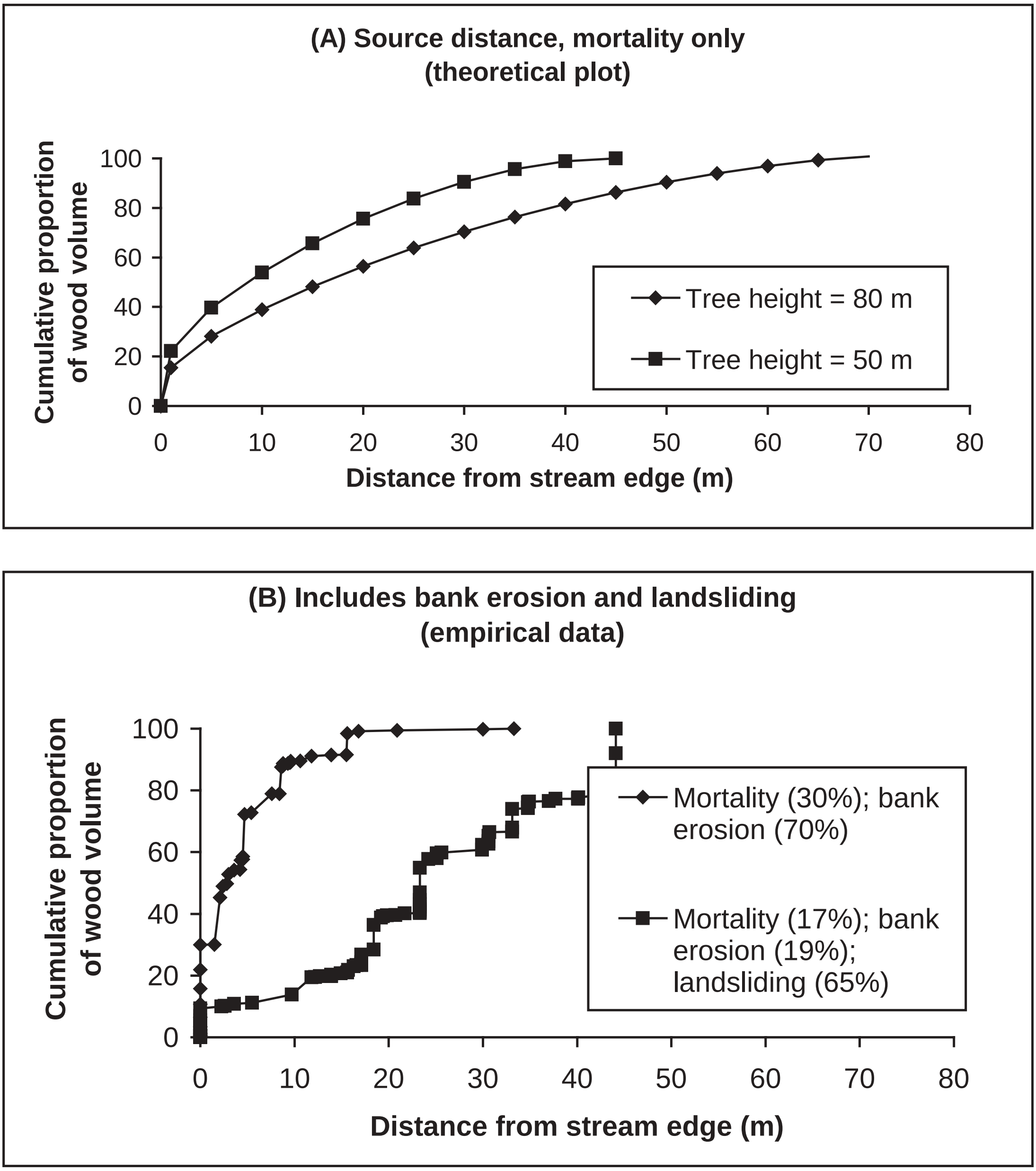
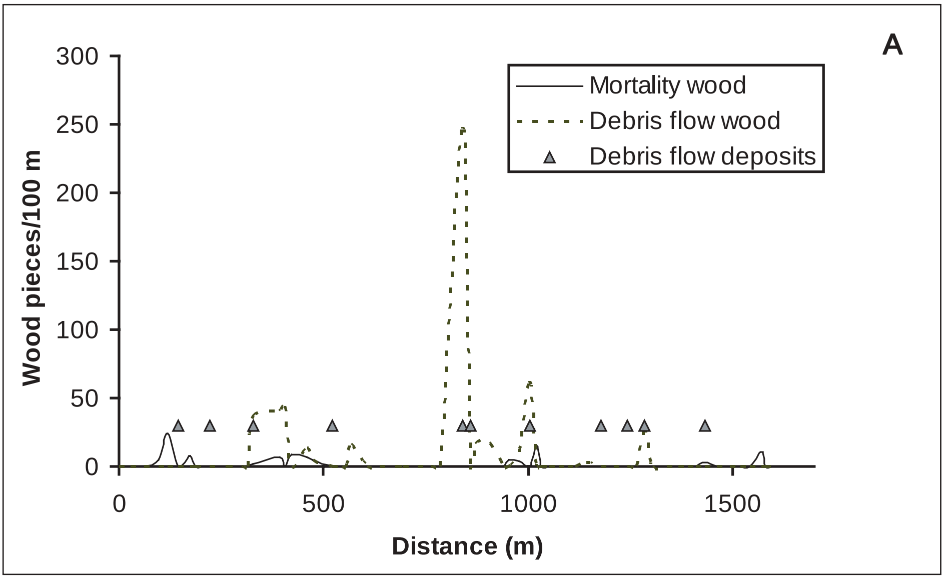



FIGURE 7. (A) Theoretical predictions of source distances are shown for chronic mortality for two different tree heights. (B) Field data reveal differences in source distances due to recruitment by bank erosion and landsliding.

## *Calculating rates of forest mortality*

Estimates of forest mortality are necessary for predicting recruitment of wood to streams and rivers (Beechie et al. 2000; Welty et al. 2002), and they may be useful to foresters and ecologists for other reasons. Forest mortality in upslope stands has been estimated by repeated surveys of stands over long periods (multiple decades). Comparable information is often not available for riparian stands, and estimating mortality rates from current stand conditions is often difficult because of problems in estimating the age of standing dead and downed trees. Mortality rates were measured in seven stands in upland forest, mid-order riparian forests, and low-order riparian



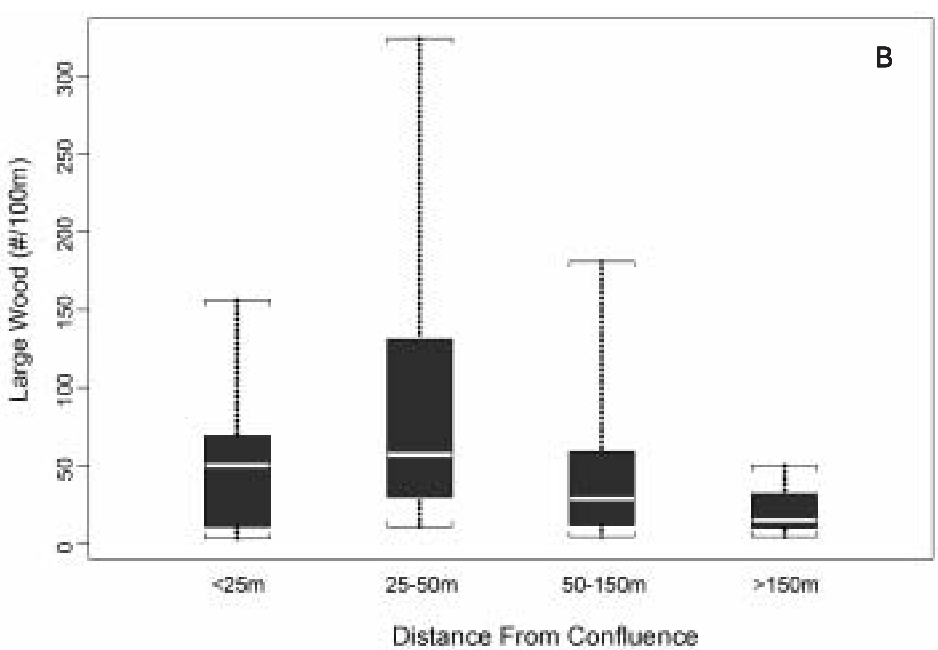




FIGURE 8. (A) Spatial distribution of wood along an unmanaged Oregon Coast Range stream (~150-years-old forest) showing clumps of wood in association with debris flow deposits. 80% of wood was originated from debris flows. (B) Wood densities along 6 km of third- and fourth-order channels in managed forests (Olympic Peninsula, Washington) increase with increasing proximity to low-order confluences prone to debris flow deposition ($P$ = 0.1) (Benda et al., in press).

forests in the western Cascades (Acker et al. 2003). Period of record was 15 years for four sites, 17 years for one site, 17 years for one site, and 7 years for one site. Average annual mortality rates for the entire period of record ranged from a low of 0.4% / year to a high of 4.4% / year. Five of the seven sites exhibited morality rates between 1.0% and 1.6% per year. The high mortality rate came from the unconstrained reach in Lookout Creek, and most of the mortality occurred as a result of trees being knocked over or swept away in the 1996 floods.

A wood budget can be used to estimate forest mortality rates in riparian forests. Solving for mortality in equation (3) requires data on wood recruitment, standing forest volume, tree height, and the proportion of tree length that intersects the channel (*P*). Generally, the temporal variability of the variables can be ignored when estimating mortality over short periods (years to a few decades). Mortality recruitment ($I_m$) is obtained from field surveys. Forest inventory surveys can be used to estimate $B_L$ and *H*. For example, standing forest biomass for Alaskan mixed spruce–hemlock is estimated at 625 $m^3$ / ha; average tree height is 20 m. In contrast, forest biomass in old-growth and second-growth redwoods can be 10,000 $m^3$ / ha (Westman and Whittaker 1975) and 500 $m^3$ / ha, respectively; average tree heights are 80 and 30 m. The *P*-values are selected from Figure 4.

Using those values in equation (3), average mortality rates in Alaska, redwood old-growth, and redwood second-growth conifer forests varied from 1.6% / year, 0.01% / year, and 1% / year (Table 2). The very low mortality rate in old-growth redwood forests is similar to one estimated by using a tree-replacement-rate estimated by Viers (1978) of two to three redwood trees per ha every 50 years (equivalent to 0.01–0.03% / year). For comparison, a forest mortality rate of 0.5% / year was estimated for mature Douglas fir forests in western Washington and Oregon using other methods (Franklin 1979). Higher mortality rates have been measured in riparian forests (Acker et al. 2003). From the data, a latitudinal control on forest mortality, as well as tree size, is apparent. For instance, mortality is highest in the forests with the smallest (spruce–hemlock) trees in southeast Alaska. Mortality is intermediate in the mid-sized Douglas fir forests in Washington and Oregon, and it is least in the largest (old-growth redwood) trees of the northern California redwoods. Mortality rates can also be estimated for inclusions of stands of deciduous trees within predominantly coniferous forests; rates of 0.02% / year and 0.6% / year for deciduous stands in old-growth and second-growth redwood forests have been documented (Benda et al. 2002). Forest mortality will also vary with forest age, a process not addressed in this example.

## *Calculating rates of bank erosion and soil creep*

Observed rates of wood input from the undercutting of banks can also be used to calculate bank-erosion or soil creep rates, though the time scale represented is constrained by equation (10). Knowledge of bank-erosion rates can aid in developing sediment budgets and in analyses of fluvial geomorphology. Estimating these rates, however, is often difficult because of the paucity of long-term field measurements or the complexity of mortality and undercutting of trees on stream-banks. Solving for bank erosion in equation (5) in southeast Alaska and in the redwood sites (Table 2) required data on wood recruitment, forest volume per unit area, tree height, and *P*. When values described previously for old-growth redwood forests were used, bank erosion was low (0.01–0.006 m / year), in part because large trees grow on a 3-m-high terrace underlain by erosion-resistant sedimentary rock. Calculated bank erosion rates in southeast Alaska were higher (0.005–0.25 m / year) and increased downstream (Martin and Benda 2001). Soil creep rates can also be estimated using a similar approach (Benda et al. 2002).

## *Predicting wood recruitment in different climatic regions*

We now apply the estimated forest mortality rates to examine how wood supply should vary with distance from stream edge for three different unmanaged forest zones along the Pacific Coast, specifically southeast Alaska spruce–hemlock forests, Washington Douglas-fir forests, and northern California redwoods. A 10-m-wide channel is used to estimate *P* for all three cases (Figure 4). For Washington's mature Douglas-fir forests, an average forest volume of 0.15 $m^3$ / $m^2$ and a tree height of 60 m is used (McArdle et al. 1961). The data in Table 2 are used for Alaska and California. Using equation (3), significant differences

TABLE 2. Calculated rates of forest mortality and bank erosion in southeast Alaska (Martin and Benda 2001) and in northern California (Benda et al. 2002).

| Alaska | Site 1 | Site 2 | Site 3 | Site 4 |
|---|---|---|---|---|
| Channel width (m) / drainage area (km$^2$) | 7 / 3.6 | 11 / 18 | 30 / 79 | 5 / 2.5 |
| Forest biomass (m$^3$ / m$^2$) / tree height (m) | 0.0625 / 20 | 0.0625 / 20 | 0.0625 / 20 | 0.0625 / 20 |
| Mortality / bank erosion recruitment (m$^3$ / km / year) | 4.41.87 | 4.711.8 | 3.70.3 | 4.63.2 |
| P: Mortality / bank erosion | 0.10 / 0.57 | 0.13 / 0.75 | 0.15 / 1.0 | 0.08 / 0.62 |
| Forest mortality (% / year) | 1.7 | 1.4 | 0.9 | 2.3 |
| Bank erosion (m / year) | 0.05 | 0.25 | 0.005 | 0.08 |
| **California** | **Site 1** | **Site 2** | **Site 3** | **Site 4** |
| Channel width (m) / drainage area (km$^2$) | 14 / 7.4 | 14 / 7.4 | 17 / 24 | 17 / 24 |
| Forest biomass (m$^3$ / m$^2$) / tree height (m) | 1.0 / 80 | 1.0 / 80 | 1.0 / 80 | 1.0 / 80 |
| Mortality / bank erosion recruitment (m$^3$ / km / year) | 2.15.9 | 01.9 | 1.21.1 | 4.22.7 |
| P: Mortality / bank erosion | 0.08 / 0.35 | 0.08 / 0.35 | 0.09 / 0.41 | 0.09 / 0.41 |
| Conifer mortality (% / year) | 0.02 | 0 | 0.013 | 0.01 |
| Bank erosion (m / year) | 0.006 | 0.01 | 0.003 | 0.01 |

appear in wood recruitment from mortality across all three regions with Washington Douglas-fir forests having the highest rates and redwoods the lowest (Figure 9), a result driven primarily by large differences in forest mortality rates. The analysis indicates how different climatic and vegetation zones can affect wood loading and storage, patterns that could be used to inform management and regulatory programs.

## *Predicting wood transport*

Field data from southeast Alaska are used in equation (9) to predict the transport distance of wood during its expected lifetime. Variables in the transport equation that need defining include $L_j$ (inter-jam spacing), $T_j$ (jam lifetime), $T_p$ (lifetime of wood in fluvial environments), and $\beta$ (proportion of a channel spanned by a jam). In Game Creek, Alaska, the distance between jams increased with increasing channel size or drainage area ($L_j$ =

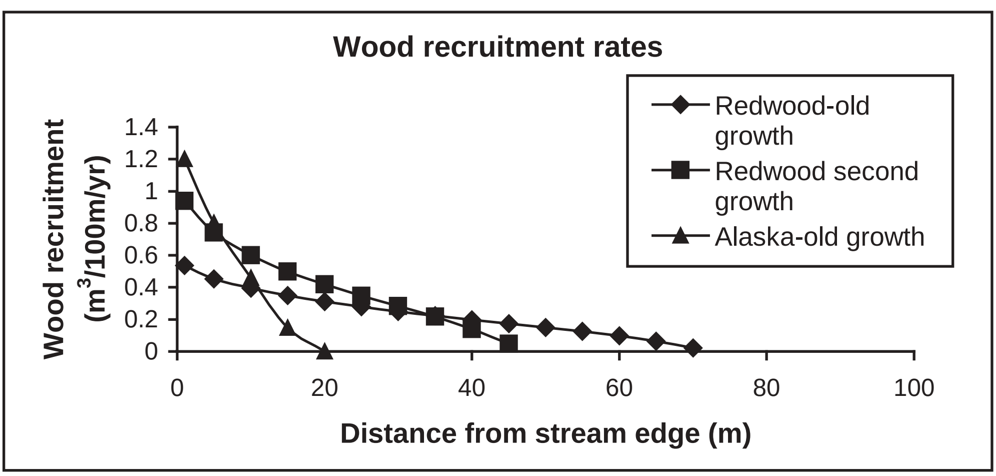



FIGURE 9. Wood recruitment rates according to distance from stream edge for three different unmanaged forest zones are predicted by using equation (3) and parameter values in Table 2.

3.28(A); $r^2 = 0.56$; Martin and Benda 2001). This relation is anticipated if the piece size distribution of wood input throughout a network remains roughly constant with increasing channel width (that is, more pieces are mobile with increasing stream width). Coinciding with this pattern is decreasing jam longevity with increasing channel size or drainage area (15–30 years in small to large channels). These patterns will, by themselves, lead to systematic increases in transport of wood with increasing drainage area.

Predicted transport distances of mobile wood (piece size < channel width) were calculated using the Alaska data described above, a $T_p$ of 100 years (based on equation (9) and using a 3% / year annual decay rate), and an average β of 0.76. Average transport distances over the lifetime of wood ranged from 100 to 300 m in the smallest streams (drainage areas < 5 km$^2$, channel width < 5 m) to 800–1,400 m in the largest channels (40–80 km$^2$ and 20–25 m wide). The predicted wood transport should impose spatial patterns on wood distribution in a watershed. For example, because lateral recruitment ($I$) depends on stream length (inter-jam distance), jam size (volume or pieces) should increase with increasing transport distance (i.e., $Q$ in equation (1)) will increase downstream). A pattern of increasing jam size with increasing drainage areas was observed in the Alaska field study and elsewhere (Likens and Bilby 1982; Bilby and Ward 1989).

## Predictive Modeling

### *Developing testable hypotheses*

Equations (1)–(9) can be used to develop hypotheses on the relative importance of different climatic or erosional regimes in the long-term (century) wood budget. To illustrate the approach here, we examine the role of two different stand-replacing fire regimes on the long-term wood budget: (1) an average fire recurrence interval of 500 years for a coastal rainforest regime, and (2) a recurrence interval of 150 years, applicable to drier landscapes. Rough approximations for the parameters in equations (3) and (4) were used in their solution, including (1) fire-killed trees topple over several decades (Agee and Huff 1987) (i.e., $T_f$ in equation (4) is 0.025 per year for $11 \leq t_f \leq 50$, where $t_f$ is time, in years, since most recent fire); (2) although hardwoods often dominate the riparian forest in the first century of growth after a stand-eliminating fire, their contribution to the total long-term wood budget is small (Harmon et al. 1986) and therefore is neglected; (3) western coniferous forests accumulate live biomass at a linear rate until about year 500, a rate that may remain stable or decline slightly thereafter (Spies et al. 1988); (4) significant mortality and therefore production of wood from large conifer trees does not begin until about a century after stand initiation (Spies et al. 1988); (5) by the first century, the majority of site potential tree height is attained (McArdle et al. 1961); (6) mortality in mature conifer forests is estimated to be 0.5% / year (Franklin 1979). The term $P$ is defined for a 10-m-wide channel, and equation (7) is used with an average annual decay rate of 3% / year.

Using this approach, large differences in the wood budget between wetter and drier forests are predicted (Benda and Sias 2003). The largest recruitment in both regions occurs immediately post fire as burnt snags topple within several decades after forest death (Figure 10). Because of the longer growth interval between disturbances, the rainforest produces a considerably larger volume of wood than the drier forest from postfire toppling of burnt snags. Moreover, the magnitude of wood recruitment associated with chronic stand mortality is significantly higher in the 500-year cycle because the constant rate of stand mortality is applied against the larger standing volume of older forests (Figure 10). Because the average time between fires in the 150-year cycle is similar to the time when significant mortality of conifers begins (100 years in our solution), the proportion of the total conifer wood supply from postfire toppling of trees in the 150-year cycle is about 50%, compared to 15% for the 500-year cycle. Finally, the range of values of wood recruitment likely to be observed is much greater in forest environments with the 500-year fire cycle compared to the 150-year fire cycle, although finding lower values of wood are more likely in the drier forest.

### *Model simulation: analysis of landscape dynamics and natural variability*

Field surveys of short durations may be insufficient to define natural variability in wood recruitment and storage, in part due to the difficult of measuring the role of rare and episodic processes in the long-term wood budget, including wildfires, windstorms, landslides, and major floods.

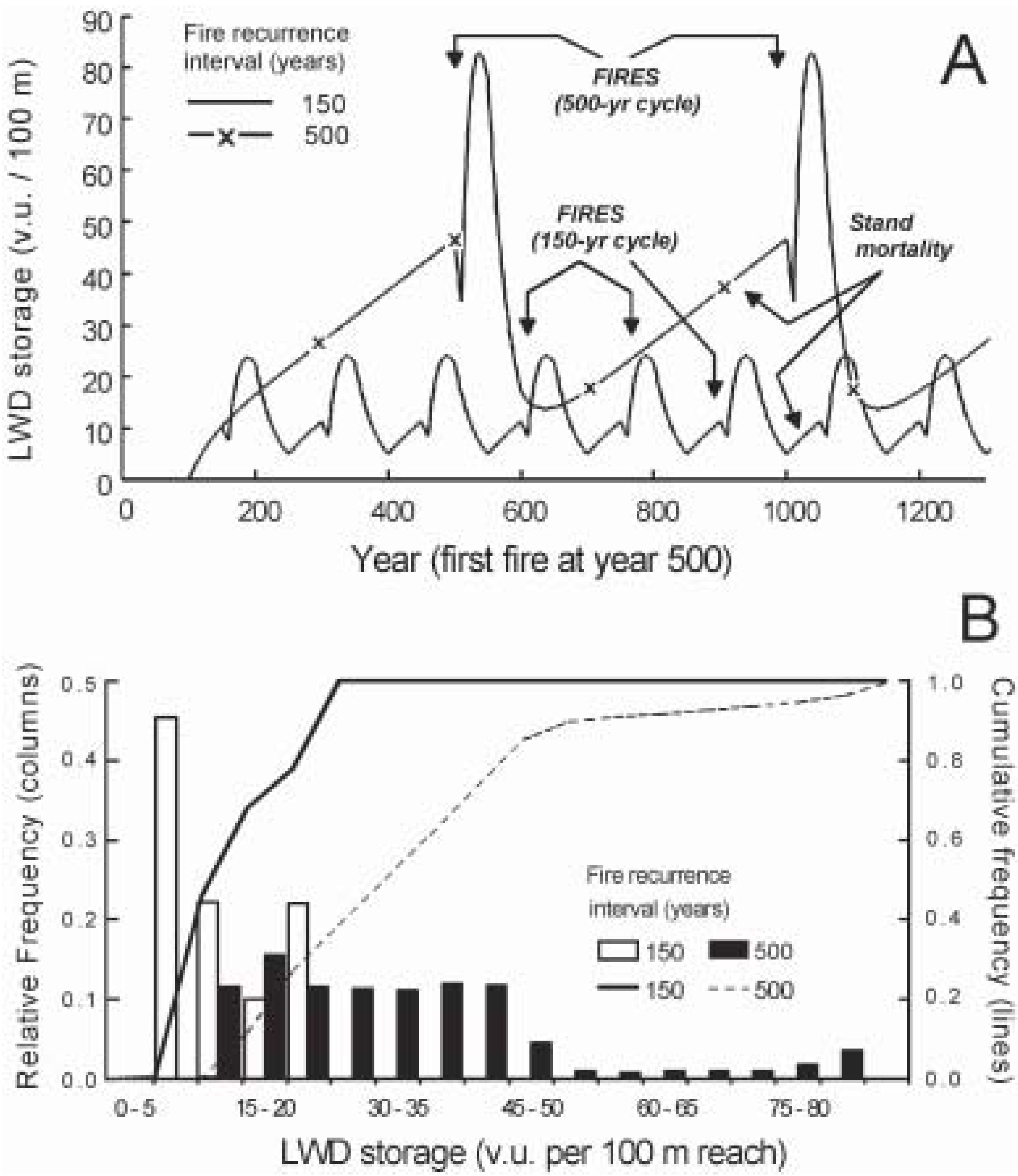



FIGURE 10. Theoretical predictions of the storage of wood for two different fire cycles. The terms $B_L$ and $B_f$ in equations (3) and (4) are expressed in arbitrary volume units (v.u.) in this exercise to avoid specifying a particular growing condition (Benda and Sias 2003).

Simulation models can be used to circumvent that limitation. To illustrate this approach, a stochastic simulation model that includes fires, storms, debris flows, and bank erosion (Benda and Dunne 1997a, 1997b) is used to solve equations (1)–(7) over a period of 4,000 years in a 200 km$^2$ watershed located in southwest Washington (USDA Forest Service 2002).

The model illustrates how disturbances (fires and storms) and forest succession can lead to marked temporal variability in wood storage (Figure 11). During periods of low disturbance (old-growth forest, no fires or large storms), wood volumes throughout most of the network are relatively low (Figure 11), with the exception of a few persistent landslide and debris flow areas. At

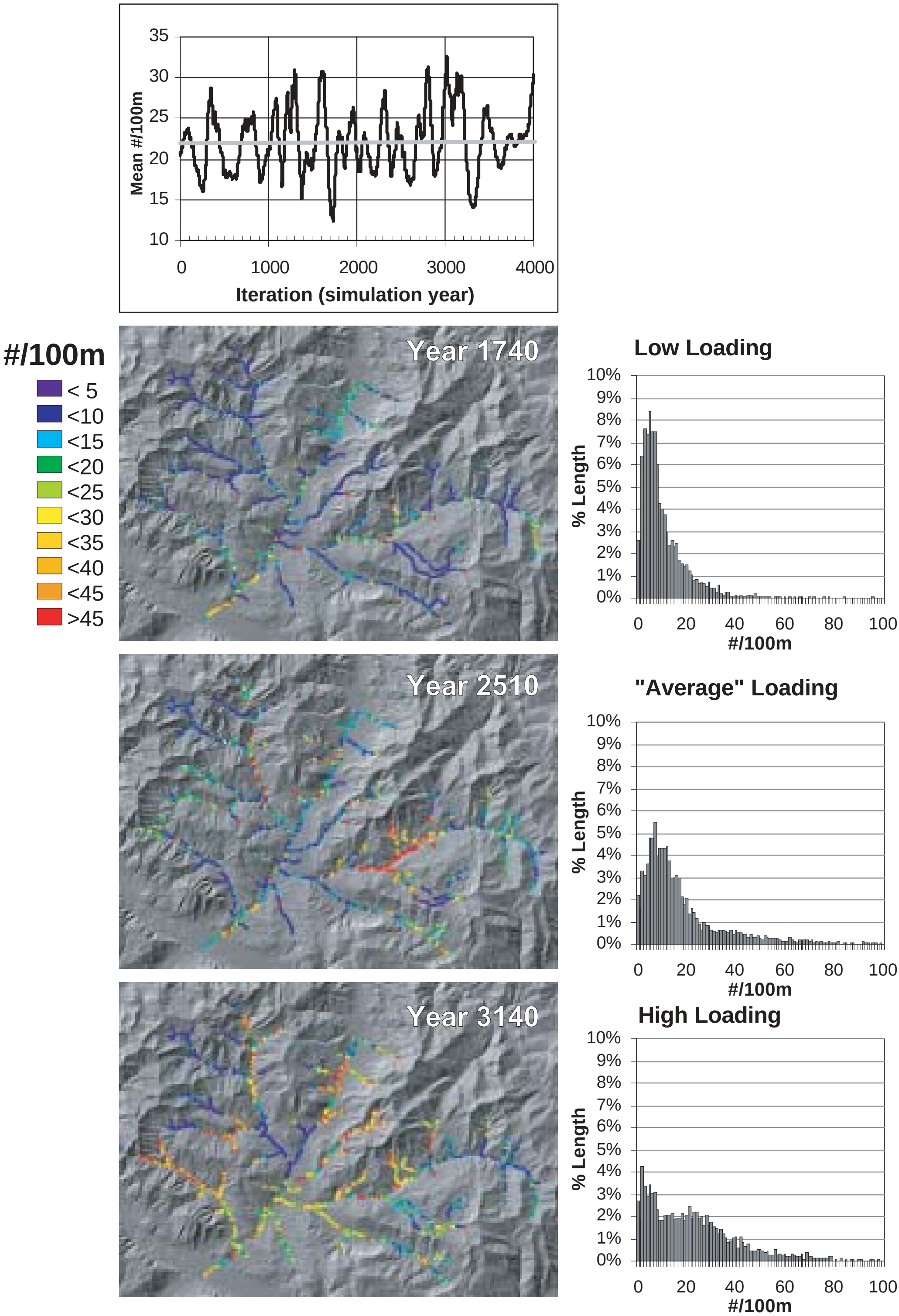



FIGURE 11. Stochastic simulation modeling of wood over 4,000 years in a 200 km² basin in southwest Washington indicates periods of high, average, and low wood storage (USDA Forest Service 2002).

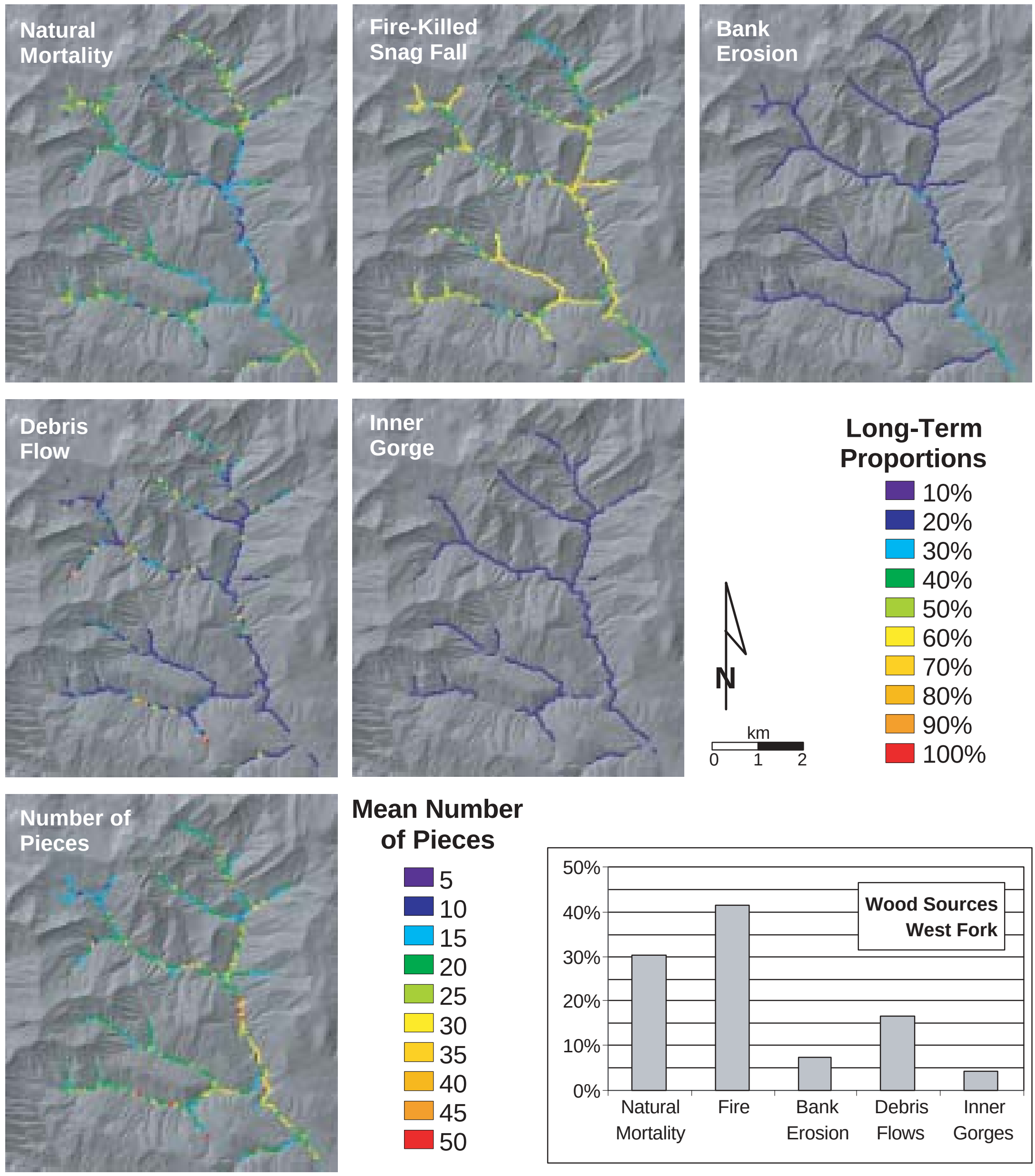



FIGURE 12. Stochastic simulation modeling of wood over 4,000 years in a 200 km$^2$ basin in southwest Washington illustrating the relative importance of five different recruitment processes and their spatial distribution (USDA Forest Service 2002).

other times, wood storage is predicted to be considerably higher. Hence, the model indicates that measures of wood storage taken at a single time reveal little about the dynamic nature of wood recruitment and storage.

Model predictions are also useful for illustrating how variation in topography (steep versus gentle hill slopes) and basin size (small versus large bank erosion rates) can create both random and systematic spatial variability in wood storage at the scale of a watershed (Figure 12). Debris flows and inner-gorge landslides create localized areas of persistently high wood loading. The model also illustrates how the proportion of wood supplied from the five recruitment processes varies spatially throughout the network (Figure 12). In some areas, fire-killed snag fall dominated, but in others, bank erosion or landsliding dominates. These types of model predictions can inform strategies that pertain to managing, restoring, regulating, and monitoring wood in streams and rivers.

## Conclusions

The predictive and testable quantitative relations among landscape process rates, their spatial variance in watersheds or across landscapes, and long-term patterns of wood abundance and distribution described in this chapter comprise a general theoretical framework for the study of wood input processes to streams. The equations can be used to construct hypotheses about wood loading across gradients in climate, basin size, topography, and land management. Anticipated shifts in wood recruitment and storage along environmental gradients can also provide keys to understanding natural variability. When applying the quantitative relations, some places may lack one or more of the processes identified here and perhaps other, less well-known processes may need to be added. Nevertheless, the general principles developed here can aid in constructing field-based wood budgets, designing simulation models, estimating the range of variability, and generating testable hypotheses on future trends of wood in rivers.

## Acknowledgments

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