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A quantitative framework for evaluating the mass balance of in-stream organic debris

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Abstract

A quantitative framework is developed for analyzing the mass budget of in-stream woody debris. Wood budgets are necessary for defining the relative importance of different recruitment processes over short and long periods, for designing spatially explicit simulation models, and for estimating the range of variability. The framework is used to analyze century-long patterns of large woody debris in streams that are governed by episodic forest death (fire and wind), forest growth and chronic mortality, bank erosion, mass wasting, decay, and stream transport. Simplified mathematical expressions are used to represent climatic, hydrologic, geomorphic, and biotic processes. Results are expressed in terms of time series and probability distributions. Predictions include that in areas of longer fire rotation (500 years) toppling of fire-killed trees comprises only 15% of the long-term wood budget yet chronic stand mortality that affect the large standing forest biomass ensures continuous large volumes of wood in streams. In contrast, toppling of fire-killed trees in forest environments with shorter fire rotations (150 years) comprise about 50% of the wood budget and indicates that field observers have a significantly higher chance of encountering low wood volumes in streams. Wood recruitment by bank erosion should increase irregularly downstream and bank erosion recruitment should exceed mortality recruitment at a bank erosion rate of approximately 5 cm per year. Recruitment from debris flows represents the single largest point source of woody debris to streams. The rarity of debris flows, in conjunction with a 3% per year annual decay rate, limits the contribution of wood from debris flows to about 12% of the long-term wood budget. Fluvial transport of wood promotes an increase in both inter-jam spacing and jam volume downstream. The proportion of woody debris transported into a reach in comparison to lateral recruitment approaches an asymptotic maximum of 50% when tree height approaches channel width. The relationships among process rates, their spatial variance across landscapes, and the resulting probability distributions of long-term patterns of wood abundance are proposed as a set of general theoretical principles. New data on wood supply and storage at the network scale are needed to fully test the predictions made in this analysis.

Keywords: Woody debris; Stream; Mass balance

1. Introduction

Large woody debris (LWD) in streams and rivers plays an important role in stream hydraulics and fluvial geomorphology and is a critical component of aquatic ecology (Swanson and Lienkaemper, 1978; Bilby, 1981; Bisson et al., 1987). Consequently, LWD has become a central theme in the management of forests and watersheds, environmental assessments, and the restoration of streams and rivers. Over 20 years of research has consistently revealed that only a relatively few processes govern the abundance and

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distribution of LWD in streams, namely forest death, forest growth, bank erosion, mass wasting, stream transport, and decay (Keller and Swanson, 1979; Spies et al., 1988; Van Sickle and Gregory, 1990). However, the study of wood supply to streams has been primarily empirical, depending on field studies conducted at the scale of reaches or stream segments (10–10^3 m) at a single point in time. As a result, relatively little is known about how LWD supply is dependent on processes that occur punctuated in time over decades to centuries, including wildfires, windstorms, landslides, and floods. This empirical deficiency, compounded by the absence of a quantitative framework for evaluating the mass balance of LWD in streams, has impeded the development of theoretical principles on how LWD supply and storage are constrained by large changes in climate (wet versus dry), topography (steep versus gentle), and basin scale (small versus large).

A quantitative framework for analyzing the mass balance of in-stream LWD is developed in this paper. The framework is used to analyze century-long patterns of LWD abundance in streams. The objective is not numerical precision about future states at individual sites but rather to produce new, testable hypotheses on the relationship between large-scale attributes of landscapes and the long-term LWD budget. The processes evaluated include punctuated forest death (i.e., fires and windstorms), forest growth and chronic mortality, bank erosion, mass wasting, fluvial transport, and wood decay (Fig. 1). Results are expressed in terms of time series and probability distributions. The quantitative framework can define what field

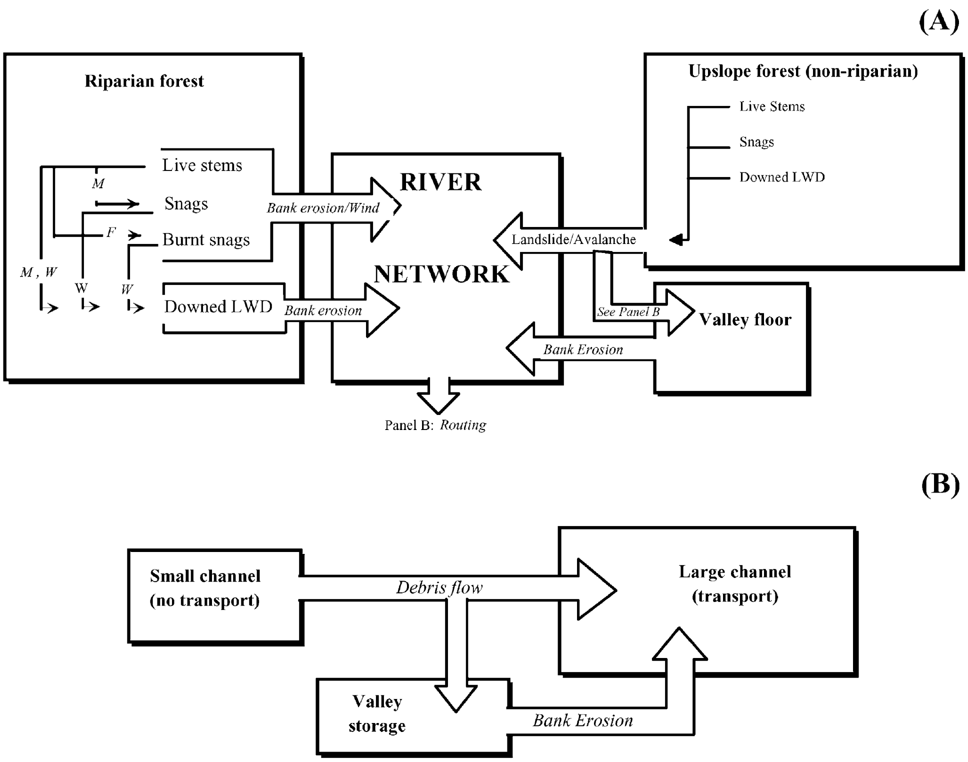

Fig. 1. The major components of an in-stream wood mass budget. (Panel A) Fire (F), wind (W), and mortality (M) convert live trees to snags, burnt snags, and downed (forest floor) coarse woody debris. In the riparian forest, wind and bank erosion transfer LWD to the river network. Bank erosion may also recruit LWD that accumulates on the forest floor. Landslides and snow avalanches recruit live and dead trees to the stream network from upslope, a portion of which may be deposited on valley floors. (Panel B) Little fluvial transport occurs in small channels because of narrow widths. However, debris flows and snow avalanches may scour the long-accumulated LWD from along small streams and deposit that material into river channels or onto valley floors. The LWD accumulations on valley floors may be recruited later to the channel through bank erosion.

measurements are necessary to construct LWD budgets within the context of large-scale spatial and temporal landscape attributes.

The paper is organized as follows. First, a quantitative framework for calculating the long-term wood mass balance is presented. Next, the equations are solved using a series of simplifications and parameter values appropriate for the Pacific Northwest region. Finally, the theoretical predictions are compared to limited available field data.

2. A quantitative framework for evaluating wood abundance in streams

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. In the watershed sciences, a familiar example is sediment budgeting (Reid and Dunne, 1996). Wood in channels also lends itself to a budgeting procedure. Constructing a wood budget requires making quantitative estimates of wood flux (volume over time per unit length of channel) from terrestrial sources (punctuated forest death, chronic forest mortality, bank erosion, landsliding, snow avalanches, etc.), wood decay, stream influx and efflux (by water transport and debris flows), and storage in channels, and on fans, terraces, and floodplains. 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, stability of debris, and residence times in channels, floodplains, fans, and terraces.

Although the term 'budget' has not been previously used to describe studies of large woody debris in streams, many studies constitute full or partial budgets. Only a partial list can be presented here. Keller and Swanson (1979) developed a conceptual and qualitative wood budget for streams in the western Cascades by identifying the major inputs, outputs, and storage reservoirs. Likens and Bilby (1982) proposed a temporal relationship among forest age, wood inputs, and the formation of wood jams. Field measurements of in-channel woody debris by Murphy and Koski (1989) defined the relative contribution from stand mortality, bank erosion, and landsliding at the stream reach scale. A watershed-scale wood budget was constructed for a 100 km^2 basin in southeast Alaska, which included predicting wood transport (Martin and Benda, 2001). Stand-level models for predicting wood loading following timber harvesting have also been developed (Beechie et al., 2000; Welty et al., 2002).

In this section, a set of general quantitative expressions are developed based on over 20 years of research on LWD that has identified the key variables and their parameter values for the Pacific Northwest. The expressions are used to examine how certain processes impose first-order constraints on century-scale patterns of LWD in streams.

The volumetric mass balance of LWD in a unit length of channel is a consequence of the differences among input, output, and decay

$$\Delta S_c = [L_i - L_o + Q_i/\Delta x - Q_o/\Delta x - D]\Delta t, \quad (1)$$

where ΔS_c is a change in storage within a reach of length Δx over the time interval Δt. Change in wood storage in a channel is a consequence of lateral wood recruitment (L_i); loss of wood due to overbank deposition in flood events and abandonment of jams (L_o); fluvial transport of wood into (Q_i) and out of (Q_o) the segment; and in situ decay (D). The L_i, L_o and D have units of volume per unit reach-length per time, and the remaining terms (Q_i and Q_o) have units of volume per time (Fig. 1).

Lateral wood recruitment to a channel segment represents several types of supply

$$L_i = I_m + I_f + I_{be} + I_s + I_e \quad (2)$$

including chronic forest mortality (I_m); toppling of trees following fires and during windstorms (I_f); punctuated inputs from bank erosion (I_{be}); wood delivered by landslides, debris flows, and snow avalanches (I_s); and exhumation of buried wood (I_e), i.e., abandoned jams and other wood deposited in alluvium and colluvium. Table 1 contains a summary of all symbols used in this paper.

The analysis of the wood budget expressed in Eqs. (1) and (2) is conducted sequentially in the following order: (1) cycles of forest death and growth; (2) decay; (3) bank erosion; (4) mass wasting; and (5) fluvial transport. The analysis emphasizes the temporal component of wood supply over centuries, although many of the processes will impose strong spatial constraints on wood abundance and distribution.

Table 1
Symbols used in the quantitative mass budget framework for in-stream large woody debris[a]

Parameter	Description	Dimensions
S_c	Instream LWD storage	$L^3\ L^{-1}$
L_i	Total lateral recruitment	$L^3\ L^{-1}\ T^{-1}$
L_o	Total lateral losses	$L^3\ L^{-1}\ T^{-1}$
Q_i	Fluvial transport input	$L^3\ T^{-1}$
Q_o	Fluvial transport output	$L^3\ T^{-1}$
D	Decay loss	$L^3\ T^{-1}$
I_m	Mortality recruitment	$L^3\ L^{-1}\ T^{-1}$
I_f	Post-fire snag fall	$L^3\ L^{-1}\ T^{-1}$
I_{be}	Bank erosion recruitment	$L^3\ L^{-1}\ T^{-1}$
I_s	Mass wasting recruitment	$L^3\ L^{-1}\ T^{-1}$
I_e	Exhumation recruitment	$L^3\ L^{-1}\ T^{-1}$
B_L	Standing biomass	$L^3\ L^{-2}$
M	Mortality rate	% T^{-1}
H	Average stand height	L
P_m or P_{be}	Stand-average fraction of LWD that intersects a channel	%
N	Number of banks contributing LWD	#
B_f	Standing burnt snag biomass	$L^3\ L^{-2}$
T_f	Annual rate of toppling of burnt snags	# T^{-1}
k_d	Annual decay rate	% T^{-1}
E	Bank erosion rate	L T^{-1}
V_s	Volume of LWD that is transported by individual mass wasting or avalance events	L^3
S_s	Storage of live and dead wood on landslide area or along avalanche path	$L^3\ L^{-2}$ or $L^3\ L^{-1}$
A_s	Landslide area	L^2
T_s	Landslide recurrence interval	T
N_s	Number of landslide source areas per unit length of channel	# L^{-1}
R_s	Delivery ratio	%
ϕ	Proportion of LWD of piece length < channel width	%
ξ	Transport distance	L
J	Inter-jam spacing	L
α	Jam longevity	T
ϑ	Lifetime of piece	T
β	Proportion of channel blocked by jam	%
μ	Piece length	L

[a] The term 'L'' refers to the dimension of length and hence L^3 refers to a volume and L^2 to an area. The term ''T'' refers to time in years.

The effect of location in a watershed on LWD abundance is described, or it can be inferred from the calculations. A detailed treatment of spatial controls that would require spatially explicit simulation modeling is beyond the scope of the present paper.

In the analysis that follows, L_o (Eq. (1)) and I_e (Eq. (2)) are treated as zero because of the absence of empirical data. Loss of wood to floodplains and abandonment of jams is likely insignificant in lower order channels because of limited sediment storage and armored banks. In larger channels, these processes would become more important. However, over periods of centuries (the scale of this analysis), loss of wood and subsequent exhumation likely balances out (i.e., $I_o = I_e$). Nevertheless, over shorter time scales, the disparity between losses and exhumation may become significant and therefore these terms are included in Eq. (1).

2.1. Punctuated forest death, forest growth and chronic mortality

Since forest disturbances influence vegetation age that in turn partially governs annual mortality rates, episodic disturbances and chronic mortality are evaluated together. Fire in pre-management forests in the mid and southern portions of the Pacific coastal ecoregion was the primary vegetative disturbance causing in many cases widespread tree death and the initiation of new forests (Agee, 1993). The average interval between stand-replacing fires, referred to as fire cycles hereafter, varied in the region from west to east of the Cascade Mountains. The effects of fire on the long-term wood budget are analyzed because sufficient information exists to define their occurrence. Equivalent information on hurricane-force windstorms, a process applicable to coastal and northern portions of the ecoregion, is not yet available but could be incorporated later.

Wildfires lead to two distinct states of wood recruitment to streams, episodic input from the toppling of fire-killed trees and chronic input from gradual stand mortality as a forest ages (i.e., by stem exclusion, suppression, disease, etc. all inputs by toppling, Fig. 1). The rate of recruitment from chronic mortality during inter-fire periods (I_m in Eq. (2)) is expressed as

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

where I_m is annual flux of LWD [$L^3\ L^{-1}\ T^{-1}$]; B_L the volume of standing live biomass per unit area [$L^3\ L^{-2}$]; M_c the rate of mortality [T^{-1}] (fraction of live biomass per unit time); H the average stand height [L]; P_m is the average fraction of stem length that becomes in-channel LWD when a riparian tree (i.e., standing within a distance H normal to the near channel bank) falls. (if source distance and fall direction are uniform random variables, then $0 < P_m < 0.5$); and N is 1 or 2, depending on whether one or both sides of the channel are forested. The procedure for estimating P_m is described in Section 3.1. By setting P_m and N to unity, Eq. (3) predicts LWD flux to the forest floor.

Recruitment of fire-killed wood (I_f in Eq. (2)) is calculated similarly as

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

where I_f is the annual flux of fire-killed trees [$L^3\ L^{-1}\ T^{-1}$]; B_f the volumetric density [$L^3\ L^{-2}$] of standing burnt snags; T_f the annual rate of toppling of burnt snags following fire [T^{-1}]; and H_f the average height of burnt snags (i.e., average stand height just prior to the last fire). B_f in the first year after fire is equal to the volumetric density of live trees just prior to the last fire.

2.2. Wood decay

Wood decay (D in Eq. (1)) limits the longevity of wood that falls onto forest floors or into stream channels, and is governed by numerous physical and biological factors. Field studies have shown that annual decay of wood in forest floor environments commonly ranges from 2 to 7% of mass loss per year (Spies et al., 1988). Streams also exert hydraulic forces that abrade wood or break the decayed and mechanically weakened organic debris into smaller transportable pieces. Estimates of annual decay rate for submerged wood range from 2 to 3%, depending on tree species (Bilby et al., 1999). Estimates of wood loss in unmanaged streams (including decay, abrasion, and transport) range between 1% (Murphy and Koski, 1989) and 3% (Hyatt and Naiman, 2001).

In this analysis, decay [$L^3\ L^{-1}\ T^{-1}$] is expressed as a simple exponential decay process (Harmon et al., 1986):

$$D(x,t) = k_d S_s, \quad (5)$$

in which k_d is annual decay loss [T^{-1}]. Wood decay occurs primarily by a loss of mass (reflected as decreasing wood density) (Hartley, 1958). However, loss of mass should equate with loss of strength and, therefore, it is assumed that wood decay in fluvial environments occurs by break-up of LWD into very small pieces that cannot be captured effectively by jams and that exit the system as floatable debris. The transformation of wood to dissolved carbon in stream water or CO_2 to the atmosphere is not considered. Transport of LWD of a length that could be captured by jams and that would add to wood stores is discussed later.

2.3. Bank erosion

Bank erosion, occurring commonly during floods, causes a punctuated supply of wood to channels (Keller and Swanson, 1979; Murphy and Koski, 1989) (Fig. 1). Bank erosion recruits trees at rates depending on erodibility of banks, flood frequency and stand density. The resistance of stream banks to erosion depends primarily on particle size of the bank material (including clay) and reinforcement by roots (Hooke, 1980). During periodic flooding, bank erosion is typically greatest in lower, actively migrating portions of channel networks and least in upper networks where banks are comprised of bedrock, boulders, cobbles, or are bounded by hillslopes. Bank erosion also occurs where flow is diverted around debris jams and other obstructions, and can occur anywhere in a channel network. Hence, the importance of bank erosion should vary strongly with position in a channel network and with flood frequency.

Mean annual wood flux due to bank erosion is expressed as

$$I_{be} = [B_L E P_{be}]N, \qquad (6)$$

where E is the mean bank erosion rate [L T^{-1}] and P_{be} [dimensionless] is the expected fraction of stem length that is deposited into the channel when a tree is toppled by bank erosion ($0 < P_{be} \leq 1.0$). P_{be} is analagous to P_m in Eqs. (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). Eq. (6) predicts annual wood recruitment for a given value of B_L. Eq. (6) could be used to predict episodic bank erosion, producing a punctuated wood influx, by treating E as a stochastic variable. Its value could be estimated from empirical information about the relationship of bank erosion rate to flood events and other watershed processes.

2.4. Mass wasting and snow avalanches

Shallow and deep-seated landslides, debris flows, and snow avalanches recruit LWD to channels and valley floors (Swanson and Lienkaemper, 1978; Benda, 1990) (Fig. 1). The importance of wood recruitment by mass wasting (I_l in Eq. (2)) depends on the type and size (area) of the landslide (or avalanche), the age (or size) of trees recruited, the number of landslide (or avalanche) source areas intersecting a channel segment of a given length, the temporal frequency of landsliding (or avalanching), and the fraction of LWD that is deposited within channels. Landslides and avalanches may deposit at least partially on fans and terraces at the base of hillslopes thereby reducing the amount of wood delivered to a channel. We express these expectatrons as

$$I_s = [V_s N_s T_s^{-1}]R_s, \qquad (7)$$

where I_s is the mean annual LWD recruitment by mass wasting or by avalanche [L^3 L^{-1} T^{-1}]; V_s is the long-term average volume of LWD that is transported by individual mass wasting or avalance events; N_s the number of landslide sites or tributaries subject to debris flows that intersect the downstream (receiving) channel [L^{-1}] (number per unit channel length); T_s the landslide or debris flow recurrence interval in years [T]; and R_s is the fraction of entrained LWD that is deposited within the channel margins. In the case of landslides, V_s is equal to $S_s A_s$, where S_s is the storage of wood [L^3 L^{-2}] on the slide area just prior to a slide event, and A_s is landslide area [L^2]. S_s represents the sum of standing live biomass (i.e., "B_L(t)") and accumulated dead wood (i.e., standing burnt snags and accumulated forest floor coarse woody debris). In the case of channelized debris flows, V_s refers to LWD stored in the channel along the entire runout path; thus V_s is equal to S_c(t) [L^3 L^{-1}] (i.e., as determined from Eq. (1)) times the mean runout path length [L]. If debris flows remove trees from the riparian stand, then this contribution will increase I_s. Although Eq. (7) predicts an average annual flux, mass wasting and avalanches occur as stochastic events; the mean volume of LWD deposited to a channel per event can be estimated by multiplying Eq. (7) by landslide recurrence interval.

2.5. Fluvial transport of wood

Wood transport depends on several factors that have been identified in field studies. Pieces that are transported tend to be shorter than bankfull width (Lienkaemper and Swanson, 1987; Nakamura and Swanson, 1993) and transport distances are limited by obstructions such as debris jams (Likens and Bilby, 1982). Because channel width increases downstream, an increasing proportion of all wood should become mobile if the distribution of instream piece sizes remains constant (Bilby and Ward, 1989). Transport of wood is also affected by stream power (slope and stream cross sectional area). Other complexities include diameter of logs, piece orientation, and the presence of root wads (Abbe and Montgomery, 1996; Braudrick and Grant, 2000).

The objective here is to minimize complexity in order to examine how a few factors (channel size, tree size, and piece size distributions) impose constraints on LWD transport and hence on spatial patterns of wood storage at the scales of watersheds over centuries. In this context, the following suppositions about wood transport are contained in the equations below. 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 LWD during the lifetime of a piece is dependent upon the lifetime of wood, the distance between transport-impeding jams, the longevity of jams, and finally the proportion of channel width spanned by jams. Hence, fluvial transport of LWD is defined here as

$$Q_{\mathrm{w}}(x,t) = [L_i(x,t) \quad \phi(x) \quad \xi(x,t)] \tag{8}$$

where Q_{w} is the volumetric wood transport or flux rate [$\mathrm{L}^3\ \mathrm{T}^{-1}$] at a cross-section within segment x in year t (equivalent to Q_{i} or Q_{o} in Eq. (1)), L_{i} the average rate of lateral recruitment [$\mathrm{L}^3\ \mathrm{L}^{-1}\ \mathrm{T}^{-1}$], ϕ the long-term proportion of all recruited LWD pieces having length (μ) less than the channel width ($w; 0 < \phi \leq 1.0$), and ξ the transport distance over the lifetime of a LWD mobile piece [L]. Eq. (8) indicates that ϕ is constant over time at a given location. Decay will tend to convert longer, non-mobile LWD to shorter, mobile pieces over time. It is assumed that the proportion of mobile LWD remains constant over time due to continuous tree recruitment (although it may vary spatially in a network). This assumption may not hold during episodes of very high or low recruitment.

We hypothesize that the lifetime of LWD can be predicted by

$$\xi(x,t) = J(x,t)\pi(x,t)\beta^{-1}(x,t), \tag{9}$$

where ξ is the mean transport distance [L] over the lifetime of a piece of wood; J the average distance between transport-impeding jams; π the larger of unity and $[\vartheta(x,t)/\alpha(x,t)]$; ϑ the lifetime in years of LWD in fluvial environments; α jam longevity in years; and β the proportion of channel spanned by a jam. Given that β cannot exceed unity, the constraint that $\pi \geq 1$ ensures that ξ cannot be less than J. This fulfills an expectation that LWD is quickly transported downstream in large floods (i.e., within a time interval $< \alpha$) until migration is impeded by a partial- or channel-spanning jam, and that LWD will tend to accumulate at jams, rather than being distributed along channel margins throughout the inter-jam space. This conceptual model does not require any consideration of flood frequency and how it changes, for example, with drainage area and climate.

In Eq. (9), transport is not limited to inter-jam spacing, but rather can become a multiple of jam spacing, for two reasons. First, longevity of mobile LWD may exceed jam longevity. Second, not all jams are channel-spanning, so that on average jams are not 100% efficient at capturing mobile LWD. The parameter β accounts for the second factor. Lacking measurements on how wood transport is affected by the proportion of a channel spanned by a jam, it seems reasonable to assume that ξ is inversely proportional to β, and that β is equal to μ/w, where μ represents the average length of jam-creating pieces, and w is channel width." The lifetime of LWD ϑ is limited by decay through a process of loss of mass. This eventually weakens logs and allows them to break apart into small, highly transportable pieces that are not susceptible to jam capture. Although loss of mass is an incremental process, it is assumed that break-up of LWD into highly transportable pieces occurs instantaneously after a time ϑ as a strength threshold is reached. Eqs. (8) and (9) apply only to streams and rivers where transport is limited by jams and they do not address transport in larger rivers where other forms of wood storage occur, such as on floodplain and in off-channel areas.

3. Theoretical predictions

In this section, Eqs. (3)–(9) are evaluated using parameter values appropriate for the Pacific Northwest. Because of the complexities involved in solving the equations over periods of centuries, some degree of simplification in description of process and parameter values is necessary. The objective in this section is to examine how LWD supply and storage are constrained by large variations in climate (wetter versus drier forests), topography (gentle versus steep, landslide-prone prone), and basin scale (large versus small) that would affect bank erosion and transport.

3.1. Punctuated forest death, forest growth and chronic mortality: role of climate

Eqs. (3) and (4) are evaluated for two different stand-replacing fire cycles: 150-years applicable to drier forest types in the Pacific Northwest region and 500-years applicable to a coastal rainforest (Douglas fir and hemlock; Agee, 1993). B_L and B_f in Eqs. (3) and (4) have units of biomass per unit area. Biomass is expressed in arbitrary units that are labeled v.u., for ''volume unit'', to avoid specifying a specific growing condition, a strategy that is designed to foster generality. This does not preclude expressing biomass in more specific units, such as cubic meters, which would require specifying a specific stand growth condition. The v.u. are transformed into LWD pieces later in the paper to compare predictions with field data. v.u. refers to that portion of a tree which has a diameter that satisfies the usual definition for LWD (Sedell and Triska, 1977).

All terms in Eqs. (3) and (4) pertaining to forests have the potential to be complex functions of time observations are used to simplify the evaluation of the equations. First, stand-replacing fires are typically crown fires that do not burn the coarse woody debris already present in a stream and on the forest floor (Spies et al., 1988). Second, fire-killed trees topple over a period of several decades (Agee and Huff, 1987) (i.e., T_f in Eq. (4) is 0.025 per year for $11 \leq t_f \leq 50$, where t_f is time in years since most recent fire). Third, although hardwoods often dominate the riparian forest in the first century of growth following a stand-eliminating fire, their contribution to the total long-term wood budget is small (Harmon et al., 1986), and therefore is neglected. Fourth, west-side coniferous forests accumulates dead biomass at a linear rate until about year 500, after which time dead biomass density may remain stable or decline slightly (Spies et al., 1988). This is consistent with an assumption that live biomass accumulates at a linear rate at least until year 500. In the solution of Eqs. (3) and (4) we assume forest growth begins the year after fire and continues at a constant rate of 10 v.u. ha^{-1} per year until year 500 and is zero thereafter. Hence, a 500 year old forest has a volumetric biomass density of 5000 v.u. ha^{-1}. Fifth, significant mortality and therefore production of LWD from large conifer trees does not begin until about a century after stand initiation (Spies et al., 1988). Sixth, by the first century the majority of a tree's maximum height is attained (McArdle and Meyer, 1961) (dH/dt is 0.4 m per year from year 1 to year 100 and 0 after). A tree height of 40 m is used to represent an average mature tree height in both west and east side environments. Seventh, mortality in mature conifer forests is estimated to be 0.005 per year (0.5% of standing trees per year; Franklin, 1979).

The remaining undefined term in Eqs. (3) and (4) is P_m. This parameter takes into account variable fall angle (not all trees will fall directly toward the channel), variable source distance (any stem within a distance H from the stream bank has the potential to contribute LWD to the channel), and breakage of tree boles upon fall. To estimate P_m, Van Sickle and Gregory's (1990) geometric fall model is applied to calculate recruited stem length for all possible combinations of source distances and fall angles (i.e., at 5 m and 1 degree increments, respectively). Fall direction is assumed to be non-preferential. For each tree fall event, the bole is assumed to break into several pieces, with piece lengths obtained by randomly sampling an exponential distribution having a mean piece length of 8 m.

Using this approach, the long-term average P_m in Eqs. (3) and (4) is predicted to be about 0.1 under the range of conditions typical of many Pacific Northwest montane streams (i.e., for channel widths in the range of 10–20 m and tree heights in the range of 20–60 m). This value is similar to the empirical value of 0.13 estimated by Van Sickle and Gregory (1990) for an old growth forest in the central Cascades of Oregon, based on 9 years of data. A time-invariant value of 0.1 is used for average P_m in calculations with Eqs. (3) and (4).

Eqs. (3) and (4) predict large differences between shorter (150-year) and longer (500-year) fire cycles when using the stated assumptions and parameter values (Fig. 2). The largest recruitment in both fire cycles occurs because of toppling of burnt snags within several decades after forest death. Because of the longer growth interval between disturbances, the rainforest (larger biomass) produces a considerably larger volume of woody debris from post-fire toppling of burnt snags. Moreover, the average rate of wood recruitment over the duration of a fire cycle is considerably higher with the longer fire cycle (Fig. 2). This occurs because the mean values of B_L, M, and H in Eq. (3) are larger in the 500-year cycle. Because the average time between fires in the 150-year cycle is similar to the time when significant chronic mortality of conifers is assumed to occur (100 years), the

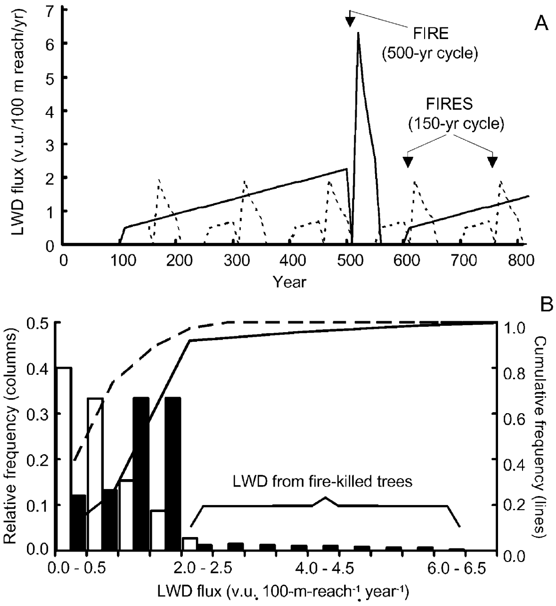

Fig. 2. The recruitment flux (volume per time) of LWD to a 100 m segment of stream for 150- and 500-year fire cycles. (A) Gradual increases in flux represent chronic stand mortality. Abrupt increases represent pulses of wood from toppling of fire-killed trees over an interval of 40 years. The abrupt decline prior to the pulse represents a cessation of growth when all trees are killed and there is a lag before toppling ensues. (B) Corresponding frequency distribution of wood flux using the entire time series (solid bars represent the 500-year cycle).

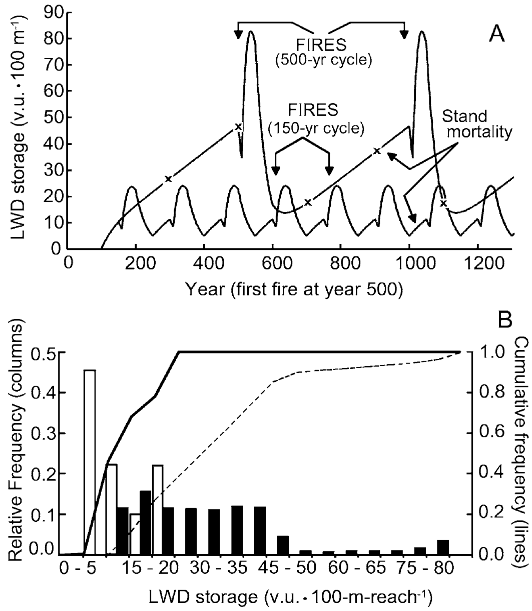

Fig. 3. (A) Patterns of wood storage for fire cycles of 150 and 500 years. Gradual increases in storage represent chronic stand mortality. The magnitude of the abrupt pulses of wood storage is governed by the amount of standing biomass (controlled by forest age) and the time interval of the toppling of fire-killed trees (40 years in this example). (B) More frequent fires result in a compressed range of variability and a shift in the distribution towards lower wood volumes (solid bars represent the 500-year cycle). Less frequent fires shift the distribution of LWD volumes towards the right into higher volumes. These patterns indicate the potential for significant differences in LWD storage along climatic gradients in the Pacific Northwest region (east to west and north to south).

proportion of the total conifer wood supply from post-fire toppling of trees in the 150-year cycle is approximately 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 (i.e., 0–6.5 v.u. ha^{-1} per year) compared to the 150-year fire cycle (i.e., 0–2.5 v.u. ha^{-1} per year). This pattern is best expressed by the probability distributions shown in Panel B of Fig. 2 as these show the significant variation in wood flux that can be anticipated along a fire frequency gradient.

3.2. *Wood decay: transforming flux into storage*

Only two processes — chronic mortality and post-fire toppling of wood — are being considered in this step of the analysis (i.e., $Q_i = Q_o = 0$ in Eq. (1) and $I_{be} = I_l = 0$ in Eq. (2)). Applying Eq. (5), the volume of wood in the active channel at the beginning of year $t+1$ is

$$S_c(x, t+1) = [I_m(x,t) + I_f(x,t) - k_d S_c(x,t)]. \qquad (10)$$

A constant 3% annual decay rate (the mid point of field measurements) allows a relatively low recruitment rate of 1–2 v.u./100 m per year (Fig. 2) to accumulate LWD stores of between 10 and 50 v.u./100 m (Fig. 3) during a 500 year fire cycle. In addition, decay limits the storage contribution of the pulsed inputs of wood during the 40-year post-fire toppling period to approximately 60 years. However, the duration of the effect from the toppling of fire-killed trees is sensitive to the decay rate. For example, a 3% average annual decay rate results in a 70% loss of wood volume after 40 years. Halving the decay rate to 1.5% increases this time to approximately 80 years and doubling the decay rate to 6% decreases the time to approximately 20 years.

Using a 3% decay rate for both fire cycles, the long-term wood storage is predicted to be much higher for the 500-year cycle compared to the 150-year cycle (Fig. 3). The probability distributions in Panel B of Fig. 3 provide the best means to interpret the predicted temporal patterns of wood storage. For example, in a 150-year fire cycle, a field observer has a significantly higher chance of encountering very low levels of LWD compared to environments with longer fire cycles, where large volumes would be commonly encountered. The predicted probability distributions in Fig. 3 suggest that there will be large differences in LWD supply and storage across climatic gradients in the Pacific Northwest region (i.e., west to east and north to south).

3.3. Bank erosion: role of basin scale

Bank erosion generally increases with increasing channel size (Hooke, 1980). Hence, the relative importance of bank erosion in a wood budget should generally increase downstream. Eq. (6) is evaluated using two bank erosion rates, 0.01 m per year indicative of small, steep mountain channels (Lehre, 1982), and 0.5 m per year representing wider, lower-gradient alluvial channels in some landscapes (i.e., channels of drainage area 10^2 to 10^3 km^2; Hooke, 1980) over a 500-year fire cycle. The P_{be} in Eq. (6) is estimated to be approximately 0.75, using the same method already described for estimating P_m, but with source distance limited to 1 m and a 100% probability of falling toward a 20 m wide channel within a 180° arc. P_{be} is very sensitive to channel width: It equals one when channel width exceeds tree height but declines rapidly with decreasing channel width. Bank erosion is assumed to occur along only one side of a channel with sediment accretion occurring on the opposite side to maintain a constant channel width over time (i.e., $N = 1$ in Eq. (6)).

Fig. 4 shows the potential importance of bank erosion in recruitment of LWD. At the low bank erosion rate (0.01 m per year), wood supply is dominated by stand mortality and punctuated inputs from episodic fires (90%). In such environments, wood recruitment and storage may be relatively low in the absence of other disturbances, such as fires, land-

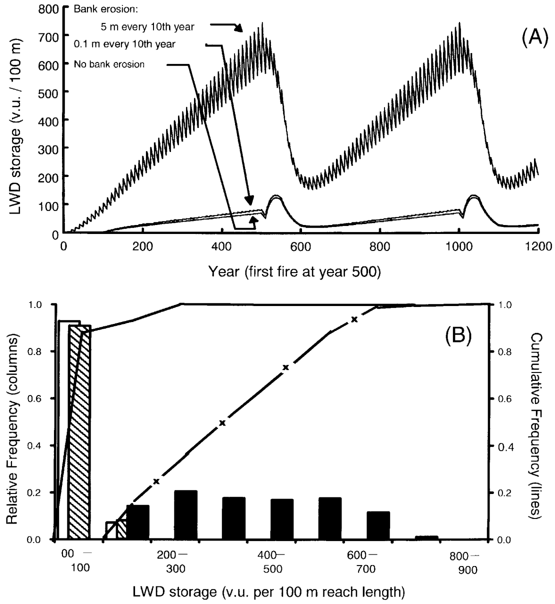

Fig. 4. (A) Effect of two different bank erosion rates on storage of large woody debris in the context of a 500-year fire cycle. A low bank erosion rate of 0.01 m per year, indicative of steep mountain channels, is almost indistinguishable from the case of no bank erosion and maintains the strongly left-skewed distribution of wood storage in (B). In contrast, the high rate of 0.5 m per year, more representative of larger, low-gradient meandering channels, completely dominates wood storage, including de-emphasizing pulsed wood from fires. The high bank erosion rate results in almost a uniform distribution of wood loading in (B) where large volumes of wood storage are predicted to occur frequently (solid bars represent the high bank erosion rate). The high frequency variation in storage (A) is the result of erosion occurring once every 10 years to mimic infrequent large floods. These patterns indicate strong spatial controls on LWD abundance in small to large drainage basins.

slides, or wind. In contrast, the higher bank erosion rate (0.5 m per year) dominates wood recruitment and yields an almost uniform distribution of storage, de-emphasizing effects of episodic disturbances, such as fires (Fig. 4). Equating Eqs. (3) and (6) predicts that bank erosion recruitment equals mortality recruitment at a bank erosion rate of 0.05 m per year on one side of a channel.

The evaluation of Eq. (6) using two extremes in bank erosion rates predicts that the importance of stand mortality should decrease downstream in a network in direct proportion to the rate of increase in bank erosion, pointing to an important spatial control on wood recruitment and storage. To determine the cross over point in a watershed where bank erosion recruitment equals or exceeds recruitment from chronic forest mortality would require detailed field measurements of LWD or the application of a mathematical relationship between bank erosion rate and drainage area. The authors are not aware of a bank erosion — drainage area relationship to estimate the cross over point in the Pacific Northwest region. A relationship between bank erosion and drainage area constructed by Hooke (1980) ($E = 0.025 \times$ (drainage area)$^{0.45}$) predicts a cross over point at about 5 km^2. Based on common experience in the region, however, this threshold drainage area appears too low. It is surmised that a bank erosion rate of approximately 0.05 m per year is probably associated with drainage areas of at least tens of square kilometers or greater in the Pacific Northwest. Field measurements of LWD or bank erosion rates at the watershed scale are needed to define the cross over point for any particular basin.

3.4. Mass wasting: role of topography

To examine the contribution of mass wasting, the analysis is limited to debris flows in steep, headwater channels because they are a relatively well-defined process (Swanson and Lienkaemper, 1978; Benda and Dunne, 1997). Debris flows episodically scour the long-accumulated woody debris and sediment from first- and second-order channels and transfer it to higher-order channels and valley floors. In this example, the product of V_s in Eq. (7) reflects the long-term expected volume of wood present in the steep, headwater tributary just prior to a debris flow. The average debris flow recurrence interval in first- and second-order channels has been estimated to be about 500 years (Benda and Dunne, 1997), indicating the value of T_s in Eq. (7). Debris flow-prone first- and second-order channels (average length about 500 m) comprise about 80% of the cumulative channel length in a typical mountain network in the Oregon Coast Range (Benda, 1990). Hence, at the scale of an entire channel network, every segment of alluvial, high-order channel of a given length has four equivalent length segments of debris flow-prone, tributary channels intersecting it. Hence, N_s in Eq. (7) is represented by the ratio of debris flow prone channels to alluvial channels, which is 4:1.

In this analysis, it is assumed that debris flows occur at the time of a fire (because of loss of root strength). (In reality, the debris flow frequency of 500 years is dictated by soil production rates, hillslope topography, and storms (Benda and Dunne, 1997)). Solving Eq. (7) with the parameters listed above at year 499 (of a 500-year fire cycle) yields an annual flux rate of 3.2 v.u./100 m per year (80 v.u./100 m $\times$ 500 m $\times$ $4 \times 1/500$ years). Multiplying the product by the debris flow recurrence interval yields the punctuated volume of 160 v.u./100 m shown in Fig. 5. Debris flows are predicted to be the single largest point source of LWD (in larger alluvial channels), because of the large store of wood that accumulates in debris flow-prone channels over the estimated 500-year average recurrence interval of debris flows (wood is assumed not to be transported by streamflow in these small,

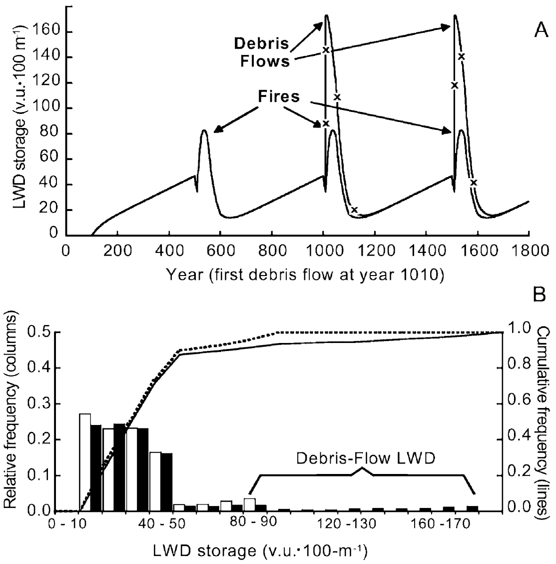

Fig. 5. The effect of debris flows in wood recruitment and storage in a 100 m reach. In this example, debris flows occur concurrent with fires (the two processes linked in time due to loss of rooting strength, Benda and Dunne, 1997) and the delivery ratio is 100% (i.e., in Eq. (8), $R_s = 1$). Debris flows every 500 years produce the largest point loading of LWD. Wood decay at 3% annually limits the effects of wood loading by debris flow because the longevity of the deposited wood of multiple decades is significantly less compared to the debris flow frequency. (B) Punctuated wood recruitment by mass wasting affects the right tail of the frequency distribution of LWD (solid bars represent fires and debris flows). Increasing debris flow frequency or decreasing LWD decay because of wood burial will increase the relative importance of mass wasting in the total LWD budget.

narrow channels, see next section). Wood decay, however, limits the longevity of wood deposited by debris flows. A decay rate of 3% yields an 80% loss of wood after approximately 60 years, a pattern similar to the decline of wood storage after fires. The time between debris flows (five centuries) compared to the short lifespan of the deposited wood (60–80 years) limits the contribution of debris flows in the long-term wood budget to about 12%. The probability distribution in Fig. 5 indicates that a field observer would encounter few debris flow deposits containing LWD except in the decades following fires and large rainstorms (in unmanaged settings). However, if debris flow frequency increased or if wood decay decreased (because of burial of wood in soil or submergence), then the relative contribution of debris flows in the wood mass balance should increase. At present, empirical frequencies of debris flows, and other forms of mass wasting, are poorly constrained. Mass wasting, or snow avalanches, should impose a strong spatial control on LWD recruitment to streams and rivers since landslide- and avalanche-prone terrains are limited to specific types of topography in a watershed.

3.5. Fluvial transport of wood: tree size and network controls on storage

Eqs. (8) and (9) were formulated to examine how a few factors (i.e., channel size, tree size, and piece distributions) constrain LWD transport, and hence, the spatial patterns of wood storage at the scale of watersheds over centuries. Solving the transport equations would require field data to parameterize ϕ, ξ, J, α, and β. Moreover, predicting transport of LWD throughout a channel network would require functions to describe relationships among those parameters and variations in channel geometry (i.e., defined by channel slope or drainage area). The field data that would allow the parameterization of those equations do not exist and new field measurements are needed to make predictions and to test them. Nevertheless, insights into spatial patterns of wood transport and wood storage can be gained by qualitatively evaluating the LWD transport equations.

Typically, channel width systematically increases with increasing drainage area (Hooke, 1980). This factor alone will cause ϕ in Eq. (8) (proportion of (I) having lengths less than channel width, i.e., mobile LWD) to increase downstream, probably in a non-linear fashion, similar to power functions relating channel width to drainage area (Fig. 6). Likewise, if the distribution of piece sizes (or tree heights) remains similar throughout a basin along the riparian zone and channel width increases downstream, there should be a consequent increase in inter-jam spacing (J in Eq. (9)). Hence, transport distance should increase downstream, probably non linearly. Other factors include the anticipated increases in total stream power and channel dimensions in channels of increasing size (i.e., increasing width and depth). This should promote a reduction in jam longevity (α in Eq. (9)). Increasing inter-jam spacing in combination with a decrease in jam longevity downstream suggest a non-linear trend of increasing LWD transport distance with increasing drainage area (Fig. 6).

These first-order constraints on LWD transport will impose certain spatial patterns of wood distribution in a watershed. First, jams should decrease in frequency downstream. However, since lateral recruitment scales with inter-jam distance, jam size (volume or pieces) should correspondingly increase with distance downstream (Fig. 6). These patterns have been observed in field studies (Likens and Bilby, 1982; Bilby and Ward, 1989).

4. Testing predictions

It is not possible to fully test the theoretical predictions made in this paper because none of the available field studies on LWD collected all of the information necessary to parameterize Eqs. (1)–(9). Moreover, there do not exist field studies that have evaluated a wood budget in terms of rates of recruitment processes at the watershed scale. Despite these limitations, available data on LWD storage are used to evaluate the general magnitudes of the predicted LWD abundance in streams. To compare the theoretical predictions with field-measured LWD, v.u. are converted to piece frequency (number of pieces per unit channel length). Piece frequency is total volume of stored wood in a channel segment divided by the volume of wood in individual pieces

$$F_{\mathrm{P}}(x,t) = \frac{S_c(x,t)}{V(x,t)}, \qquad (11)$$

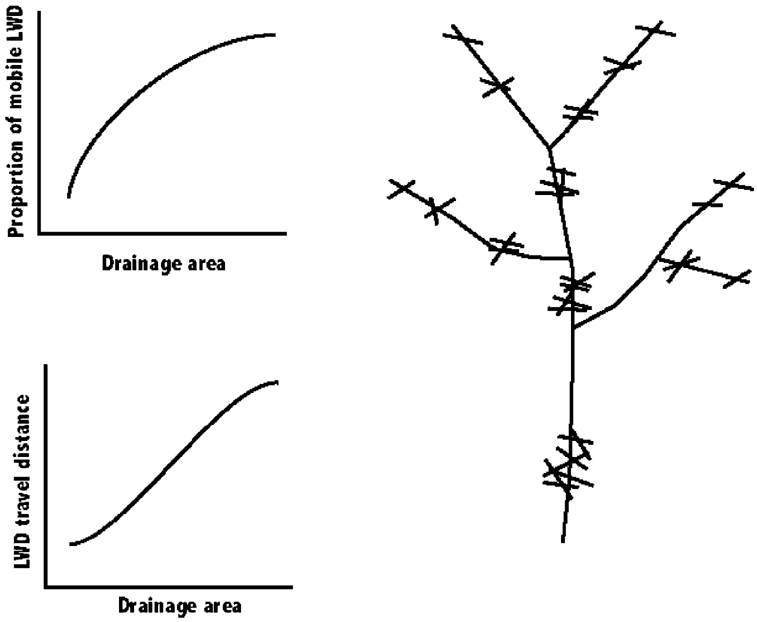

Fig. 6. First-order constraints on the fluvial transport of LWD in streams include stream size (width), tree height, and the distribution of piece lengths. As channel width increases downstream, an increasing proportion of LWD will become mobile (i.e., piece length < channel width). This pattern should result in the formation of fewer transport obstructing jams with increasing distance downstream. Because lateral recruitment of LWD scales with channel length, an increasing inter-jam spacing should lead to larger jams downstream (volume or pieces).

where F_P is piece frequency per unit channel length, S the total wood volume per unit channel length, V the amount of wood contained in each piece (v.u. per piece), and t the time since last fire (or stand age) in years.

$$V(x,t) = \left[\frac{B_L(x,t)}{SD}\right]\left[\frac{H}{\mu}\right] \quad (12)$$

where SD is stem density (number of standing live trees per unit area) and μ refers to average piece length.

The change over time in piece frequency is complicated by temporal patterns of stand growth, tree height, mortality, and breakage patterns. To circumvent those complications, Eqs. (11) and (12) are solved using average constants for stand density, tree height, and piece length representative of mature, coniferous forests. Stand density in mature, Pacific coastal forests commonly ranges between 200 and 400 trees ha^{-1} (McArdle and Meyer, 1961; Lienkaemper and Swanson, 1987). It is assumed that stand density is 250 trees ha^{-1}, H is 40 m, B_L is 5000 v.u. ha^{-1} (i.e., using values for H and B_L that correspond to a 500 year-old forest), and μ is 8 m (Heimann, 1988). A 40 m-tall tree is equivalent to five pieces of 8-m-long woody debris. With these assumptions, average piece size (v.u. per piece) increases with stand age. For example, each 8 m piece of new LWD recruit contains 0.7 v.u. in year 100 and 3.5 v.u. in year 500, equivalent to smaller diameter woody debris in young forests and larger diameter pieces in older forests.

Fig. 7 shows wood storage expressed in terms of piece frequency for three cases: (1) a 500-year fire cycle that includes chronic mortality and toppling of fire-killed trees; (2) case 1 adding debris flows; and (3) case 1 adding bank erosion ($E = 0.01$ m per year). These scenarios do not include fluvial transport. For all three scenarios, the number of pieces of wood per 100 m segment is about 10 in young forests. Mortality in the absence of debris flows and bank erosion yields a relatively constant 20 pieces per 100 m for a mature forest, a consequence of wood storage and piece volume increasing at similar rates such that their ratio remains almost constant. Bank erosion increases piece frequency to 25 per 100 m except following fires when piece frequency increases to 45 per 100 m.

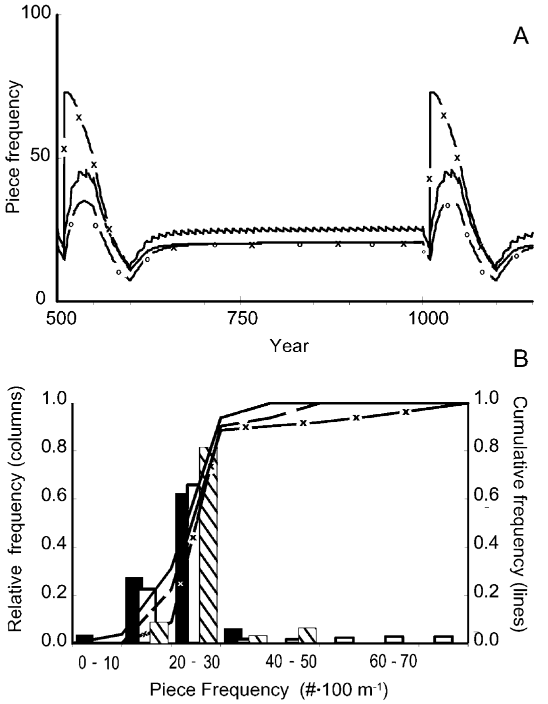

Fig. 7. (A) Frequency of pieces of large woody debris per 100 m channel segment that represents three cases: (1) fires and mortality (lines with circles); (2) case 1 including 1 cm per year bank erosion (solid line); and (3) case 1 with debris flows every 500 years (lines with 'x's'). An annual decay rate of 3% is used and stream transport of wood is omitted. Fires and mortality alone yield a relatively constant 20 pieces per 100 m over most of the cycle. Fires and debris flows increase piece frequencies to 30 and 70 respectively. Long-term mean piece frequencies for the three cases are 20, 24, and 25, respectively. (B) Probability distribution of piece frequencies. The predicted piece frequencies are similar to field measured values (see text).

Debris flows occurring concurrently with fire yields 70 pieces per 100 m. Long-term mean piece frequencies for the three different cases are 20, 24, and 25 pieces per 100 m, respectively.

The predicted piece frequencies are similar to field measured values in unmanaged areas. For example, Bilby and Ward (1989) measured a range of 10–60 pieces (average of 24) of woody debris per 100 m reach length in channels between 4 and 20 m wide in southwestern Washington. In southeast Alaska, Robison and Beschta (1990) measured piece frequencies ranging from 25 to 42 per 100 m in streams between 4 and 13 m wide. Six other studies, summarized by Peterson et al. (1992), revealed 11–60 pieces (average 40) per 100 m in streams 4–20 m wide. The similarity between the predicted range of piece frequencies and field measurements indicate that the theoretical analysis provided here is sufficient to reproduce values of wood loading that occur in nature. This may be a consequence of two factors. First, the general magnitudes of process rates (fire cycles, bank erosion, debris flows, decay rates, etc.) that occur in nature constrain the magnitude of S in Eq. (11). This establishes the correct range of piece frequencies. Secondly, empirical data supports relatively narrow ranges for stand density, tree heights, geometric pattern of tree fall, and mean fragment length, and these narrow ranges may constrain the absolute magnitude of piece frequencies.

5. Conclusions

Over 20 years of research into LWD in streams have consistently identified the importance of six processes in controlling abundance and distribution of LWD in streams, namely episodic forest death, forest growth and chronic mortality, bank erosion, mass wasting, decay, and stream transport (Fig. 1). Despite this consensus, almost no field studies have evaluated the relative importance of these factors in governing the mass balance of LWD in streams over long periods or large regions. The absence of this understanding is exacerbated by an absence of predictive quantitative theory in the study of LWD in streams over large temporal and spatial scales. The objective of this paper is to address those limitations by formulating testable mathematical expressions that address the first-order constraints that major processes impose on wood abundance and distribution. Although numerous small-scale complexities were not addressed in order to make the calculations over large temporal scales tractable, these omissions likely comprise second-order effects compared to the effects that large variations in climate, topography, and basin scale have on LWD abundance (i.e., the purpose of this paper).

The quantitative framework presented in this paper is useful for defining the field measurements that are necessary to construct empirical mass budgets of LWD in streams in any region (Martin and Benda, 2001; Benda et al., 2002). In addition, the mathematical expressions and analyses provide a temporal and spatial context from which to view measurements obtained over short time periods and in small areas. Testing the predictions will require additional measurements, in addition to LWD storage, of the specified parameters at the scale of entire watersheds and perhaps space-for-time substitution.

The predictive and testable quantitative relationships among process rates, their spatial variance in watersheds and across landscapes, and long-term patterns of wood abundance and distribution (in the form of probability distributions) presented here are proposed as a set of general theoretical principles. Although the temporal patterns of the various processes are emphasized, several of the processes impose strong spatial constraints on wood abundance and distribution, including bank erosion, mass wasting, and fluvial transport. We have indicated how these controls may play out in a watershed. Spatially explicit modeling is required for further analysis of the spatial controls of wood abundance (Benda et al., in press) and is beyond the scope of the present paper. The equations and their general solutions for the Pacific Northwest provide hypotheses about wood loading as one traverses gradients in climate (wet versus dry), basin size (small versus large), and topography (gentle versus steep). Anticipated shifts in probability distributions along those gradients provide keys to understanding natural variability in wood flux and storage in streams and rivers.

When applying the quantitative relationships presented here, parameter values may need to be tailored to other landscapes and regions. In some places, one or more of the processes identified here may not occur and perhaps other, less well-known processes may need to be added. The general principles developed in this paper can aid in constructing wood budgets, designing simulation models, estimating the range of variability, and generating testable hypotheses on future trends of LWD. For example, interregional differences in wood abundance could be linked to differences in climate, vegetation, land-cover history (including effects of fire, land management, or climatically induced cover change), and topography.This research was funded by Earth Systems Institute (www.Earthsystems.net), Washington Forest Protection Association, US Bureau of Land Management, and USDA Forest Service. This work has benefited from discussions with a number of talented individuals, including Robert Bilby, Thomas Dunne, Dan Miller, Curt Veldhuisen, and Douglas Martin and from comments of anonymous reviewers.

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