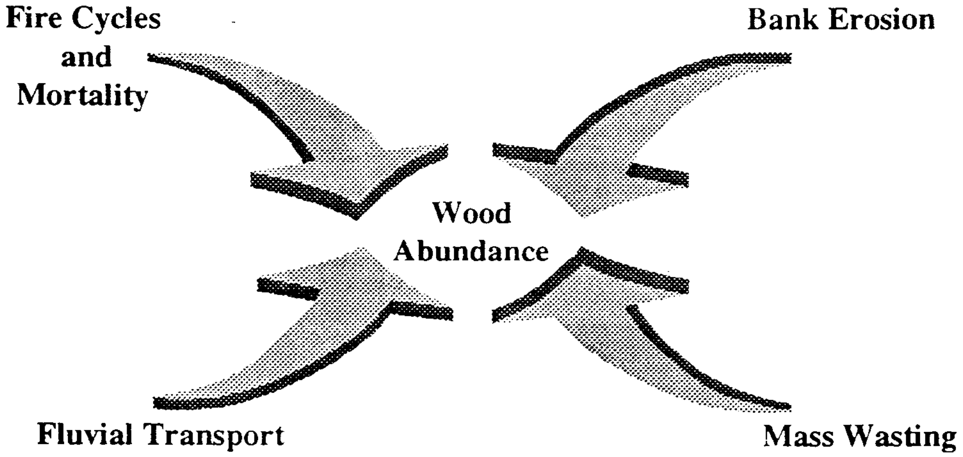
LANDSCAPE CONTROLS
ON
WOOD ABUNDANCE
IN
STREAMS



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Acknowledgements

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Abstract

Storage of large woody debris in streams is variable in time and space because wood recruitment and transport are driven by episodic disturbances that occur over cycles of decades to centuries. Collecting information on woody debris by strictly empirical means is hindered by time limitations of field studies and complexities of natural environments. As a consequence, the range and magnitude of variability of wood in streams are not well constrained. To circumvent those limitations, long-term patterns of wood recruitment, transport, and storage are evaluated by employing simplified expressions to represent climatic, biotic, and geomorphic processes. Five universal landscape processes that govern wood storage are considered: (1) Frequency of stand-resetting disturbances and subsequent trajectories of forest biomass accumulation and stand mortality; (2) intensity of bank erosion and its spatial variance in a network; (3) temporal and spatial frequency of mass wasting; (4) fluvial transport controlled by number of upstream contributing segments and wood loss through export or valley floor storage; and (5) rates of wood decay. The structure of variability in wood abundance, in the form of frequency distributions, is predictably constrained by the general magnitude of landscape process rates and vegetative characteristics of streamside forests. Variations in these attributes within individual watersheds and across different regions alter patterns of wood abundance. Relationships among landscape process rates, their spatial variance in a basin or landscape, and the resulting shapes of frequency distributions of wood recruitment and storage constitute a set of general theoretical principles which have practical applications, including: (i) Providing a framework for constructing wood budgets, including estimating the range and magnitude of variability in wood abundance; (ii) generating testable hypotheses on current wood loading and future trends; and (iii) setting realistic targets for future wood recruitment and storage.

1.0 Introduction

Large organic debris in streams and rivers has been recognized as an important component in aquatic ecology, fishery habitat biology, geomorphology, hydrology, and forestry over the past several decades. Woody debris in streams regulates and stores dissolved and particulate matter (Bilby, 1981) and creates temporary reservoirs of coarse sediment, thereby altering local channel gradients and channel morphology (Heede, 1972; Megahan and Nowlin, 1976; Keller and Swanson, 1979; Bisson et al., 1987; Montgomery et al., 1995). Deposits of sediment stored behind logs create spawning areas for fish (Keller and Tally, 1979; Sullivan, et al., 1987). Pools formed in association with wood function as rearing and feeding areas for fish in the summer and as critical low-velocity refuge habitat in the winter (Swanson et al., 1976; Lilse and Kelsey, 1982; Dolloff, 1983). As a consequence, the role of woody debris in fish habitat and stream ecology has become a central theme in the management of forests (Femat, 1993), environmental assessments (WFPB, 1997), and the restoration of streams and rivers (Collins et al., 1994; Beechie et al., 1995).

Despite the importance of woody debris in streams, there remains relatively little information on how wood abundance is linked to landscape processes which have temporal cycles of activity of decades to centuries. This has hindered the development of quantitative theoretical principles on wood abundance in streams. A number of important issues need to be resolved in order to develop such general principles:

5) What are the effects of episodic disturbances, such as fires and wind, on long-term wood supply, and how do these effects vary among landscapes?

2) How important are landslide and debris flow disturbances in the recruitment of wood?

3) What is the relative importance of stand mortality versus bank erosion in wood supply and how does it vary throughout a network?

4) How does stream transport of wood and valley storage change the supply of wood downstream from first- through higher-order channels?

5) What degree of spatial and temporal variability in wood recruitment and storage occurs as a consequence of the factors listed above?

A preliminary descriptive framework for addressing these five issues in the larger context of a wood mass balance in streams can be built by a review of relevant literature. Fires and windstorms of varying intensity and size result in cycles of forest death causing infrequent concentrated toppling of trees (Harmon et al., 1986; Agee and Huff, 1987). In the wake of disturbances, trajectories of forest growth, biomass accumulation, and mortality strongly influences the production of coarse woody debris (Spies et al., 1988). Bank erosion and landsliding, controlled by topography and the precipitation climate of a watershed, add a punctuated supply of wood to streams and rivers (Swanson and Lienkaemper, 1978; Keller and Swanson; 1979). These stochastic processes occur over landscapes with considerable spatial variability in topography and forest cover, the legacy of earlier climatic and geomorphic disturbances. Hence, wood recruitment to a channel network occurs as a complex series of discreet events.

Woody debris enters a channel network that is convergent and hierarchical (Horton, 1945). Downstream transport of wood depends on piece size, channel width, and stream energy (Lienkaemper and Swanson, 1987). Some fallen trees, whole or in pieces, span the channel and create temporary blockages, resulting in non-uniform storage of wood in jams. Conversely, smaller pieces of wood are transported downstream and become redistributed throughout the channel network. Hence, a channel network integrates numerous wood sources, and the resulting change in wood flux and storage downstream is dependent on the geometry of individual reaches, number of upstream contributing channel segments, and wood loss through export and off-channel storage on floodplains and terraces.

Biological decay and physical abrasion cause pieces of woody debris in streams to have finite life spans. Decay of wood and abrasion depends on regional and micro-climates, specie and size of organic material, and stream energy (Harmon et al., 1986; Maser et al., 1988). Burial of wood in soil or submergence in streams delays decay and abrasion, and increases the longevity of woody debris (Nanson, 1981; Triska, 1984). Hence, the wood mass balance or wood budget (volumetric change over time over some channel length) is governed by the rate of stochastic inputs by episodic fire and wind, forest stand mortality, bank erosion, landsliding, and fluvial inputs, minus the rate of fluvial export, storage on valley floors, wood decay and abrasion.

The recruitment and storage of wood over years to centuries is highly variable and unpredictable at the scale of stream reaches (10^2 m) or networks (10^6 m) because of the complex and stochastic factors listed above. Hence, it is difficult to define the full structure of variability in woody debris in streams by field measurements alone since only a single point in time is considered. In this study, the complexities inherent in the study of woody debris that occur over large time and space scales are circumvented by coarse-graining (Gell-Man, 1994), a tactic which employs simplified expressions to represent multivariate and complex landscape processes (Benda and Dunne, 1997). Five universal landscape processes are evaluated with the objective of developing quantitative theoretical principles on woody debris in streams applicable to Pacific Northwest landscapes: (1) Cycles of forest death and growth; (2) bank erosion; (3) mass wasting; (4) fluvial transport and valley floor storage; and (5) wood decay. Relationships among landscape process rates and wood abundance are represented in the form of frequency distributions. Although much interest in large woody debris in streams is centered around managed forests, our analysis is limited to conditions likely occurring in unmanaged environments. Information on natural variability can provide an important context from which to interpret large woody debris in managed watersheds.

2.0 Framework: Five Landscape Processes

Because fires, wind, and floods both recruit trees to streams and initiate new forests, the time scale over which to consider long-term wood recruitment, transport, and storage is decades to centuries. Furthermore, because stream transport integrates numerous wood sources, the appropriate spatial scale is the channel network (i.e., watershed). Five universal landscape processes are considered:

5) Vegetative disturbances, such as fires and wind, cause cycles of forest death which lead to punctuated inputs of wood to channels. Stand-replacing disturbances establish a trajectory of forest growth, biomass accumulation, and stand mortality which affect the rate of recruitment of wood to streams.

2) Bank erosion recruits trees to channels at a rate depending on flood frequency and magnitude, and the erodibility of banks. Bank erosion rates vary greatly with position in a channel network and generally increase downstream.

3) Landslides and debris flows add a punctuated supply of wood to channels and valley floors. The relative contribution of landsliding to the wood supply is dependent on landslide frequency and on how many landslide sites intersect a channel of a given length.

4) Biological decay and physical abrasion strongly influence the longevity of wood in streams, and are dependent on macro- and micro-climates, vegetative species, and stream energy.

5) Transport of woody debris integrates numerous wood sources and leads to an increasing wood flux downstream. Logs that span channels inhibit wood transport and create jams. Wood can be abandoned on terraces and floodplains by floods or channel meandering.

The importance of these five factors on wood recruitment and storage has been identified in previous studies (Keller and Swanson, 1979; Franklin, 1979; Bilby and Likens, 1980; Beschta, 1983; Bisson and Nielson, 1982; Swanson et al., 1982; Harmon et al., 1986; Murphy and Koski, 1989; Maser et al., 1988; Spies et al., 1988; Van Sickle and Gregory, 1990, among others to numerous to cite here). In this paper, we build upon that body of work by developing simple functions that characterize the five landscape factors to evaluate how process rates reported in the literature constrain the abundance and natural variability in wood loading and storage over periods of decades to centuries. Results are presented in the form of frequency distributions (and cumulative distribution plots which are not as sensitive to bin size). The terms range of variability refers to the spread of the values in the distribution and magnitude refers to either the mean or maximum. For example, frequency distributions inform on how often high values of wood storage can be expected to occur in comparison to lower values, and comparison between distributions allows us to evaluate the role of the five landscape factors in governing wood abundance in streams.

3.0 Mass Balance of Large Organic Debris in Streams and Rivers

The change in storage of large organic debris in a channel segment over time, as governed by the five landscape factors, is a consequence of the difference among input, output, and decay processes, i.e., the annual mass balance for woody debris can be written as:

$$V_W(k,t) - V_W(k, t-1) = I_W(k,t) - D_O(k,t) + Q_{WI}(k,t) - Q_{WO}(k,t) - S_O(k,t) \qquad (1)$$

where the left side of (1) is the change in the volume of wood from one year (t-1) to the next (t) in segment k. Specifically, $V_W(k,t)$ represents the wood volume at the end of year (t), and all terms on the right-hand side (defined below) represent the total flux during that year. In equation 1 and in all that follow time is reset to zero after each stand-initiating disturbance.

The term I_W in equation 1 represents the three landscape factors that control wood recruitment:

$$I_W (k,t) = I_{WM} (k,t) + I_{WF} (k,t) + I_{WB} (k,t) + I_{WL} (k,t) \quad . \qquad (2)$$

These are natural stand mortality (I_{WM}); pulses of wood following stand-replacing disturbances, such as fire and wind (I_{WF}); bank erosion (I_{WB}); and stochastically occurring landslides, debris flows, or snow avalanches (I_{WL}). D_0 represents biological decay and physical abrasion and breakup. Fluvial transport of wood into and out of the reach is represented by the terms Q_{WI} and Q_{WO}. S_O represents a loss of wood through transferal and abandonment on floodplains and terraces by floods and channel meandering. An illustration of the wood mass balance is shown in Figure 1.

Wood recruitment and storage sequences, and their statistical distributions, are assessed using Equation 1 and the integral of Equation 1. This requires estimating each of the eight variables represented in the right hand sides of Equations 1 and 2 using parameters that are relevant to Pacific Northwest landscapes. The effect of each of the five landscape processes on wood recruitment and storage are examined individually and include the following cases: (1) Wood recruitment (flux) from streamside forests, when fire and mortality are the only sources; (2) wood storage corresponding to case 1 that is mediated by different decay rates; (3); case 2 with the addition of variable bank erosion rates; (4) addition of debris flows; and (5) the effect of fluvial wood transport on wood storage patterns. The sequential analysis of each of the five landscape processes enable us to estimate the relative contributions of fires, chronic mortality, bank erosion, debris flows, and transport to the long and short term wood budget. Equations for estimating independent variables are presented when the variable is invoked for a particular case.

In pursuit of generality and to examine the *relative strength* of the five landscape factors in modifying the long-term frequency distribution of wood storage, predictions are expressed in arbitrary units of wood volume, referred to as v.u. (volume units). Use of arbitrary volume units also avoids having to limit our analysis to a specific growing condition and to a corresponding absolute value of wood storage. Biomass units are converted to number of pieces of wood per channel length (piece frequency) for the purpose of comparing theoretical predictions with field measurements later in this paper.

3.1 Cycles of Forest Death and Growth: Consequences for Wood Recruitment

Fires in pre-management forests in the mid and southern portions of the Pacific Northwest are the primary vegetative disturbance, causing in many cases widespread tree death and the initiation of new forests (Swanson et al., 1988; Agee, 1993). Frequency of stand-replacing fires, referred to as fire cycles, varies in the region from west to east because orographic effects decrease precipitation and increase occurrence of droughts, and from north to south because of increasing temperature and occurrence of

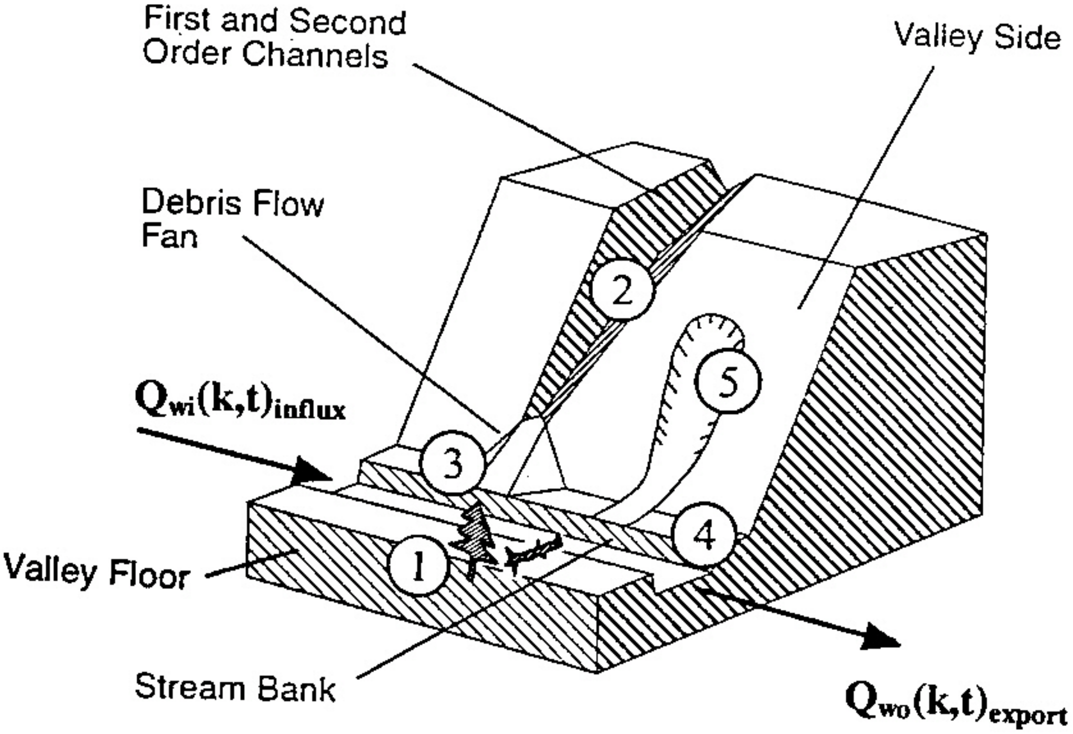


Figure 1. Illustration of the wood mass balance governed by the universal landscape processes of (1) stand mortality and fire-pulsed wood, (2 & 5) debris flows and streamside landslides, and (3 & 4) bank erosion along terrace and fan margins. Stream influx and export of wood is shown as Q_{WI} and Q_{WO}, respectively.

lightning (Agee, 1993). Fire regimes are strongly affected by topography (e.g., south-facing slopes burn more frequently than wide valley floors) and hence disturbance cycles may vary with topographic position (Swanson et al., 1988; Benda et al., 1998, Figure 11.5). Effect of fire on the long-term wood budget is analyzed because sufficient information exists to define their cycles. Equivalent information on catastrophic wind disturbances in the region is not yet available but could be incorporated later.

3.1.1 Analysis of Disturbance Cycles

The effect of two end-member fire regimes on variability in wood loading are examined: A 500-year cycle associated with the wettest forests on the west-side of the cascades (Agee, 1993), and a cycle of 150 years applicable to drier areas in the southern cascades of Oregon (Agee, 1993) and in eastern Washington. Fires can be expected to lead to two distinct states of wood recruitment, a chronic input from gradual stand mortality as a forest ages, and a punctuated input from the toppling of fire-killed trees. Although forest growth, mortality, and distributions of tree heights have the potential to be complex functions of time, we apply a series of simplifications about them that are consistent with the published literature. The basis of these assumptions are the following observations: (1) Change of forest biomass over time can reasonably be represented as a linear function since stand initiation (Bormann and Likens, 1979, pg. 167), which is consistent with a linear rate of coarse woody debris accumulation on forest floors (Spies et al., 1988, pg. 1697; Sias et al., 1998); (2) mortality in mature coniferous west-side forests has been estimated to be about 0.5% annually (Franklin, 1979); (3) significant mortality in conifer forests does not begin until about year 100 (Spies et al., 1988), at which time the majority of tree height is attained (McCardle et al., 1961); and (4) fire-killed trees topple over a period of several decades (Agee and Huff, 1987).

Recruitment from chronic mortality (I_{WM}) was calculated at an annual time increment for 100 meter reaches with the following equation:

$$I_{WM}(t,k) = B(t,k) * M(t,k) * H(t,k) * P(t,k) * 2 * 10^{-2} \qquad (3)$$

where t is the number of years since stand growth began for any segment (k) within a network. The first three terms on the right hand side account for stand growth dynamics: Standing biomass per unit area (B(t,k)); annual mortality rate (M(t,k)); and average stem height (H(t,k)), respectively. P(t,k) is the proportion of a fallen tree that intersects a channel which represents random fall direction, variable source distance, and fragmentation upon fall, processes described below. Wood recruitment calculated for both sides of a channel requires a multiplier of 2, and 10^{-2} is required to present volume in terms of 100 m reaches. Post-fire recruitment of wood (I_{WF}) is calculated using Equation 3, subject to the condition that 100 percent of the stems present at the time of fire are killed, and then topple over a specified interval of time, beginning some time after a fire, i.e.

$$I_{WF}(t,k) = B_F * M_F * H_F * P * 2 * 10^{-2}, \tag{4}$$

where B_F and H_F are the values of biomass per unit area and tree height just prior to the fire, and M_F (post-fire annual rate of toppling of burned snags) is 1.0 / toppling period. Based on Agee and Huff (1987), a reasonable toppling period is 40 years beginning 10 years after a fire (i.e., $11 < t < 50$). This and all following equations apply to any channel segment in a network allowing us to omit the term (k) in the remainder of the equations.

In Equations 3 and 4, I_{WM} and I_{WF} have units of v.u. / 100 m segment / year, provided that each term is expressed in the following units: B (and B_F) as v.u./hectare (ha); M_F as year $^{-1}$ (proportion of trees that die each year); H (and H_F) as meters; and P is dimensionless. Biomass per unit area in volume units (v.u.) in (B) and (B_F) refers only to that portion of a tree which exceeds some minimum dimensions corresponding to large organic debris, typically two meters in length and 0.1 m in diameter at both ends (Sedell and Triska, 1977).

The term (P) in Equations 3 and 4 represents the average fraction of stem length that enters a channel when a tree topples. Fallen trees may contribute less than their entire length to a channel, depending on their distance from the channel and the direction of fall (Figure 2), relationships first proposed by Murphy and Koski (1989) and used by VanSickle and Gregory (1990) to predict flux rates to a reach of stream in Oregon adjacent to an old growth forest. The latter researchers found poor agreement between the predicted and observed flux for a nine-year period, and attributed the difference to the fact that their model did not include breakage of stems upon fall (woody debris was assumed to be added as whole trees in their model). We use results from the model of Sias et al. (1998) to account for stem breakage wherein effect of fragmentation is included by assuming all falling trees break into pieces having sizes that are representative of piece size distributions collected in Pacific Northwest streams by Heimann (1988) and Veldhuisen (1990). Specifically, the largest piece occurs near the base of the tree and progressively smaller pieces (all piece sizes selected from the empirical distribution) occur towards the crown. In our estimate of P, any piece that enters the channel or overlaps either bank is assumed to contribute to the channel store of wood, a conservative estimate. Combining fragmentation with random treefall adjacent to a 10 m wide channel yields an stand-averaged value for P of about 0.1 (i.e., averaging over all possible source distances and fall angles, only 10%, on average for all trees, of a tree length encounters the stream channel). This model predicts that P is only weakly sensitive to channel widths in the range of 5 to 15 m and tree heights in the range of 30 to 50 m, i.e. for conditions representative of many channel networks in mountainous landscapes in the Pacific Northwest (Sias et al., 1998).

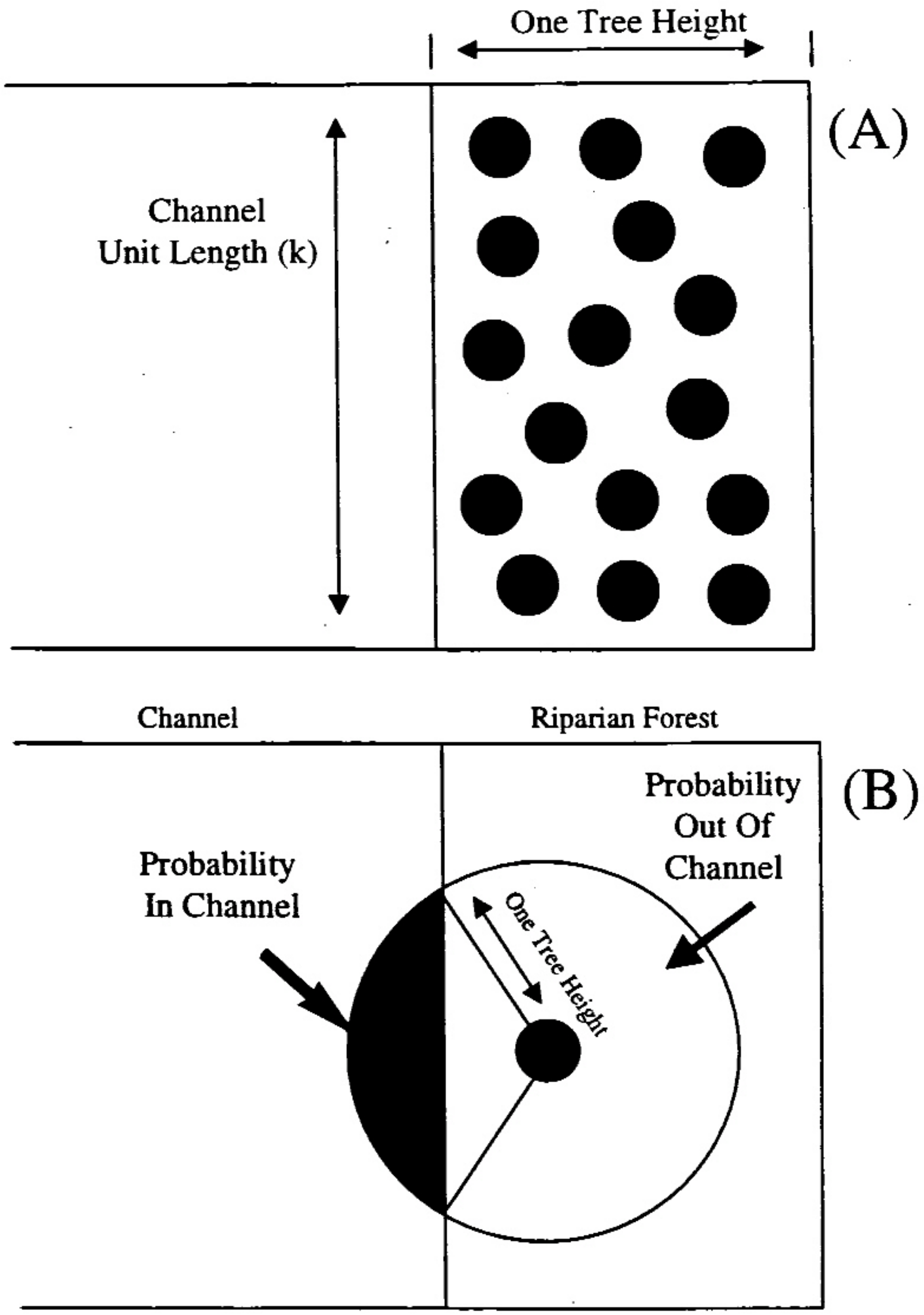


Figure 2. (A) A streamside forest situated on a valley floor with dimensions of streamwise unit length and width of one tree height. The streamside forest contains uniformly-spaced and sized trees where all trees grow at the same rate. (B) Summing the proportion of the 360° fall radius of all trees that could encounter the channel for each of the uniformly spaced and sized trees gives the stand-average proportion of a tree length that can intersect a channel (about 10% for a 10 m wide channel).

The linear increase in forest biomass (the rate arbitrarily set at 10 v.u. per year) in conjunction with a constant mortality, a constant proportion of stem length that contributes to a channel, and a constant tree height of 45 m yields a linear increase in recruitment of large wood over time. Although the use of single values for some of the variables to be estimated in Equations 3 and 4 are simplifications of complex processes, prediction of a linear recruitment or flux rate is consistent with empirical chronosequences of forest floor storage of coarse woody debris in the Pacific Northwest until at least age 500 (Spies et al., 1988). The low mortality rate (0.005/yr) and low proportion of stem length that can enter a channel (0.1) severely limits the amount of biomass that becomes large woody debris. For example, a 200 year-old forest with a biomass per unit area of 2000 v.u. / ha (i.e., 200 years $*$ 10 v.u. / ha) corresponds to a wood recruitment rate of 0.8 v.u. per 100 m-long channel per year (e.g., four hundredths of one percent of the standing biomass enters the channel each year from a one hectare area along both sides of a 10 m wide channel).

3.1.2 Effects of Disturbance Cycles on Wood Supply

Our analysis of wood recruitment begins at forest age 100 because significant mortality of conifer trees in the form of large woody debris does not occur until that time (Spies et al., 1988; Sias et al., 1998) (higher production of smaller pieces is expected because of suppression mortality of small trees in young forests). In stands less than a century old, mortality and the recruitment of wood may be dominated by relatively small hardwood trees (Grette, 1985; Heimann, 1988). In unmanaged watersheds, hardwood trees may dominate in areas frequently disturbed by floods and sedimentation events. Young deciduous trees also dominate riparian forests in managed watersheds due to historical clearcut logging. As a consequence, models of wood recruitment for young managed forests have been developed (Kennard and Pess, 1998). Although hardwood trees may be important in some environments, their contribution to the total wood budget is volumetrically quite low in conifer-dominated stands when forest growth extends over multiple centuries (Spies et al., 1988; Sias et al., 1998). We limited our analysis to the recruitment of conifer coarse woody debris which does not begin until after the first century of forest growth.

The linear increase in recruitment as a function of forest age yields significant differences in wood loading between the 150- and 500-year fire cycles (Figure 3). The magnitude of chronic recruitment of coarse woody debris from gradual stand mortality, and from pulses of fire-killed trees, scales with the amount of standing biomass during inter-fire periods. Magnitude of wood recruitment associated with chronic stand mortality is higher in the 500-year cycle because the constant rate of stand mortality is applied against the larger standing biomass of older forests. In addition, pulses of wood recruitment are significantly greater in the 500-year fire cycle because post-fire tree fall is proportional to volume of standing biomass divided by the time required for snags to topple (Equation 4). To generalize, longer fire

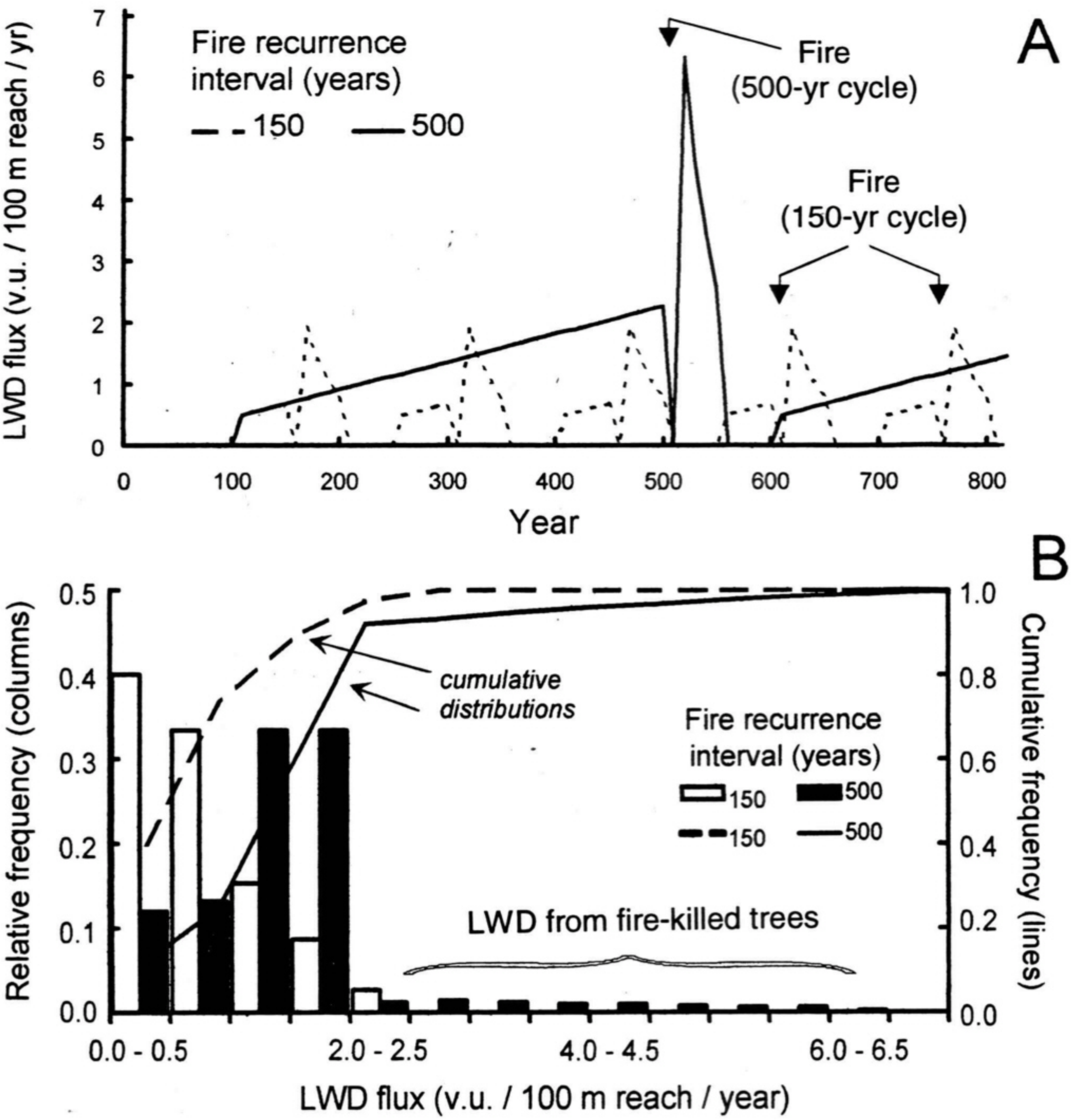


Figure 3. Decadal flux of large woody debris to a 100 m segment of stream for 150 and 500 fire cycles. (A) Gradual increases in flux represent chronic stand mortality. Abrupt increases in the time series represent pulses of wood from toppling of fire-killed trees over an interval of 40 years. The abrupt decline prior to the pulse represents a cessation of growth (and therefore mortality) when all trees are killed and there is a lag before toppling ensues. (B) Corresponding frequency distributions of wood flux. The cumulative distribution is also shown because unlike the histogram representation, the appearance of the cumulative distribution is not highly sensitive to bin size. The predicted shapes of the flux time series and distributions are independent of the choice of volume units.

cycles yield longer periods of larger recruitment rates, larger maximum recruitment rates post fire, and greater temporal variability in wood supply (Figure 3B). Drier forests with more frequent fires have longer periods of low wood recruitment, lower maximum post-fire wood pulses, and lower natural variability in wood supply. These differences are also apparent in the shapes of frequency distributions of wood recruitment for the two different fire regimes. The distribution of the 150 year fire cycle is positively skewed with values truncated in the lower range. In contrast, the distribution of the 500 year cycle is more uniform with a tail that extends towards the right into the larger volumes thereby increasing the range and magnitude of variability.

3.2 Wood Decay and Abrasion: Consequences for Wood Storage

Wood decay ($D_O(k,t)$ in Equation 1) limits the longevity of wood that falls onto forest floors, or into stream channels, and is governed by numerous factors, including temperature, humidity, precipitation, and the size and specie of woody debris (Means et al., 1985). Field studies have shown that annual losses of wood in forest floor environments commonly range from 2 to 7% per year (Spies et al., 1988). Submergence of wood in streams and rivers can delay decomposition and reduce the rate of wood loss from that measured in terrestrial environments (Nanson, 1981; Triska, 1984). However, streams exert hydraulic forces which abrade wood or breakup decayed and mechanically weakened organic debris into smaller, highly transportable pieces. Estimates of wood decay rates in streams from field studies have ranged between 1 and 6% (Murphy and Koski, 1989; Hyatt, 1998).

Under the condition of no stream transport and no loss of wood to off-channel storage, the governing equation for the volume of wood in the active channel is given by the cumulative wood recruitment less the cumulative decay (i.e. Equation 1 with $Q_{WI} = Qwo = S_O = 0$). If cumulative decay is calculated according to a simple exponential decay law for which there is much empirical justification (Harmon et al., 1986), then

$$D_O(t) = k_d * V_W(t) \qquad (5)$$

in which k_d is annual fractional decay loss and $V_W(t)$ is the total volume of wood stored in the channel. Hence, wood storage in a particular year t+1 is

$$V_W(t+1) = (1-k_d)[V_W(t) + I_{WM}(t) + I_{WF}(t)] \qquad (6)$$

The relationship between forest biomass, recruitment of coarse woody debris, decay (using a 3% annual rate, the mid point of field estimates), and storage over a fire cycle is shown in Figure 4. Initially, recruitment occurs at a greater rate than decay, and wood accumulates over time. If the fire recurrence interval is long enough, then eventually the annual decay loss equals annual input (when $I_{WM}(t) = k_d * V_W(t)$) and at that time storage attains a constant value. The pulsed input of wood during the 40 year toppling period following fire contributes significantly to storage for approximately 80 years.

The duration of the pulsed wood from toppling of fire-killed trees is very sensitive to the decay rate (Figure 5). 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 this time to approximately 20 years. With respect to entire fire cycles, variation in decay rates is expressed as dramatic changes in the frequency distributions of wood storage (Figure 6). Decreasing decay rates from 6% to 1.5% annually shifts the distribution to the right thereby expanding the distribution and increasing the range and magnitude of variability.

The relationship between the two fire cycles and wood abundance, including range and magnitude of variability, can now be evaluated. Although the 500-cycle yields larger amounts of wood post fire because of higher standing biomass, the contribution to the overall wood budget is low, about 15%, because of longer periods of higher chronic recruitment (Figure 7). In contrast, the contribution from fire-pulsed wood to total wood storage in the 150 year cycle is about 50%, a consequence of the similarity between fire frequency and timing of significant suppression mortality of conifers (e.g., 100 years). The frequency distribution of wood storage for the 150 year cycle is positively skewed, reflecting the increased occurrence of lower volumes of wood and that frequent fires recruit a large proportion of the total wood supply to streams. As a result, the frequency distribution has a compressed range and magnitude of variability. The 500 year cycle, in contrast, is characterized by a more uniform distribution of wood storage (Figure 7,B), a consequence of the longer periods of larger forest biomass, larger recruitment rates, and the decreasing volumetric importance of fire-pulsed wood. To generalize, increasing disturbance shifts the distribution of wood storage towards the left and compresses the range and magnitude of variability while decreasing rates of disturbance (e.g., longer fire cycles) expands the range and magnitude of variability. Over short human lifetimes, this effect may be observed as one travels from watershed to watershed within a similar physiographic area, in essence encountering a range of disturbance histories. However, over short time frames (decades) in localized areas, more variability may be observed in more frequently disturbed environments because of the higher probability of encountering infrequent events. Although our estimate of wood storage in arbitrary volume units provides insights into the range and magnitude of variability in different environmental settings, they cannot be directly compared to field measurements. Predictions of wood storage are converted to piece frequency (number per 100 meters) later in the paper so that predictions can be compared to real environments.

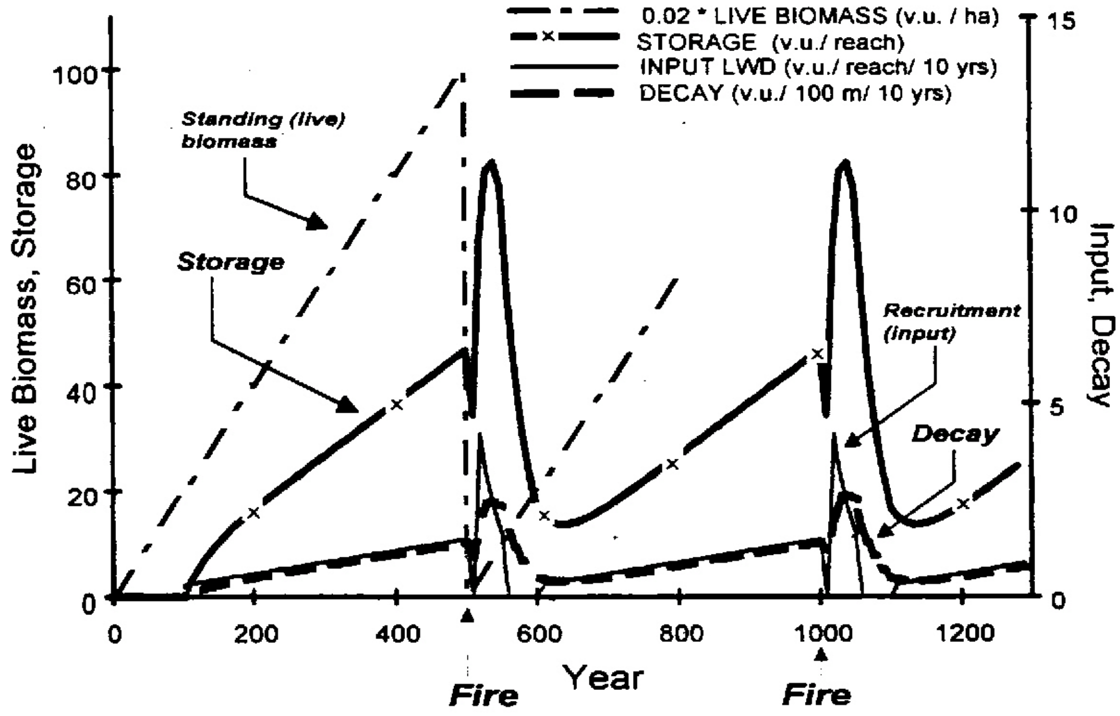


Figure 4. Simulated relationship between standing live riparian biomass and storage of large woody debris in 100 m length channel, in the absence of fluvial transport. Storage at any time is equal to the cumulative input less cumulative decay. In this example, fires occur every 500 years, live biomass is converted to woody debris at 0.5% per year, fire-killed trees fall uniformly over a period of 40 years, and only about 10% of the stem length (on average) of trees encounters the 10 m wide stream channel. Wood decay is 3% annually, the mid point of field measurements. Note the different patterns between input (recruitment) and storage, which represents the accumulating volume of undecayed wood over time.

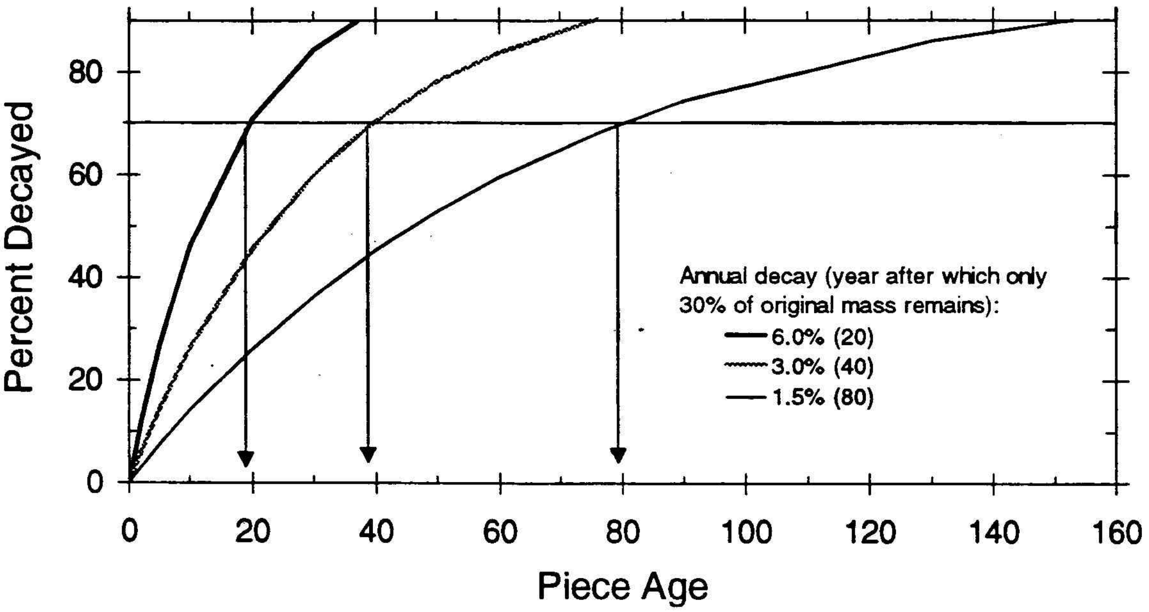


Figure 5. Amount of wood decay over time for three different annual decay rates. Seventy percent of an original wood volume is decayed after 20 years using a 6% rate compared to 80 years with an annual decay rate of 1.5%.

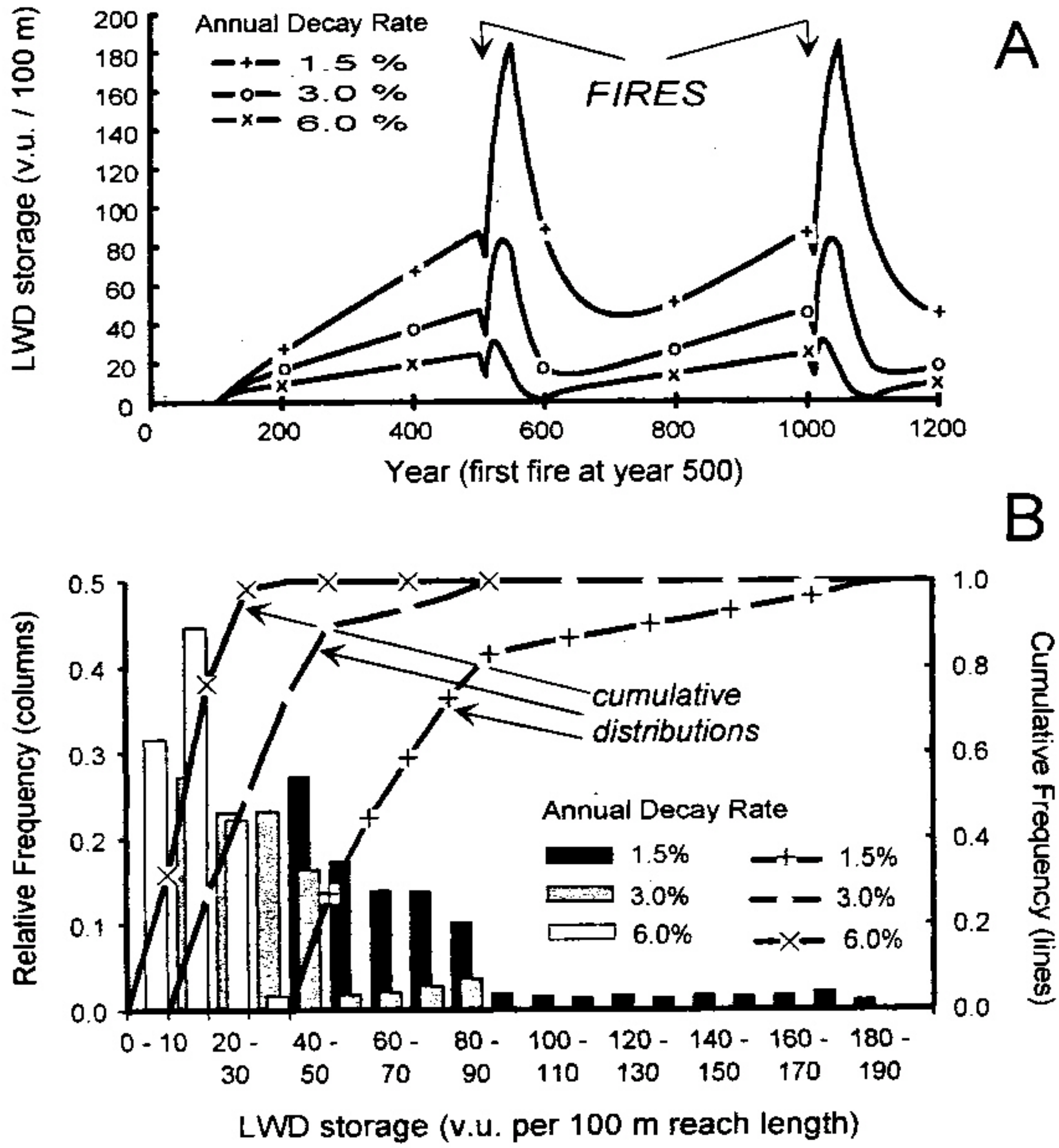


Figure 6. (A) Patterns of storage for the 500 year fire cycle for three different annual decay rates. The legacy of wood recruitment from the toppling of fire-killed trees extends almost 150 years with a decay rate of 1.5%, and drops to little over 50 years with a rate of 6%. Physical breakup and transport of mechanically weakened woody debris would likely reduce the time wood from fire pulses would survive in channels. Likewise, the storage of wood from chronic stand mortality is also greatly affected by variation in decay rates. (B) Corresponding frequency distributions of wood storage for the three decay rates. Decreasing decay rates shifts the distributions towards the right side into the region of higher volumes of wood, while increasing decay compresses the range and magnitude of variability in wood storage.

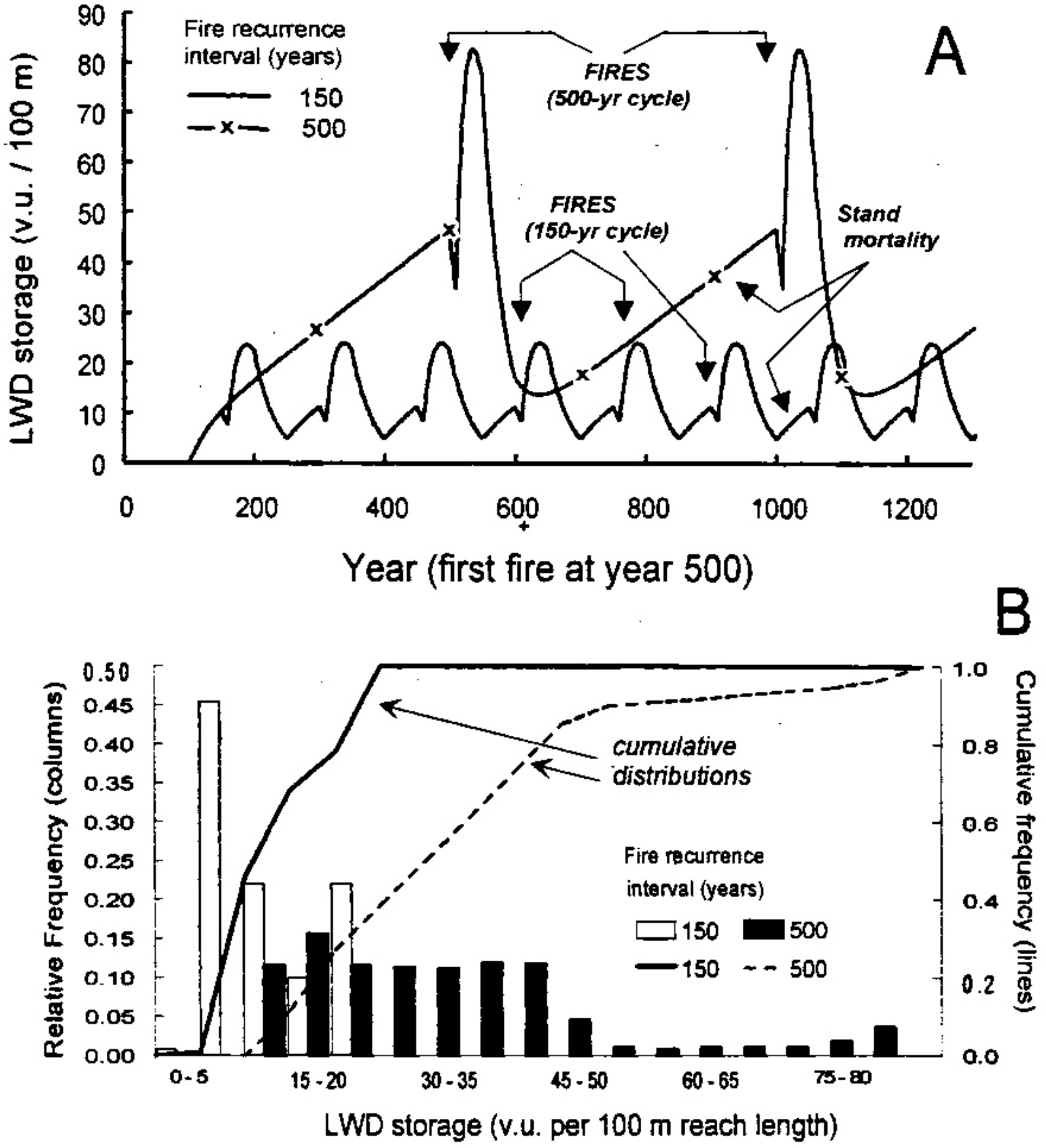


Figure 7. (A) Patterns of wood storage for two end member fire cycles of 150 and 500 years. Gradual increases in storage represent chronic stand mortality. The magnitude of the abrupt pulses of wood storage is governed by the amount of standing biomass (controlled by forest age) and the time interval of the toppling of fire-killed trees (40 years in this example). Hence, the pulse of wood in the 500-year cycle is greater than in the 150-year cycle because of the larger standing biomass of the older forest. (B) Corresponding frequency histograms of wood storage and cumulative frequency distributions. More frequent fires results in a positively-skewed distribution with compressed range of variability while less frequent fires lead to a more uniform distribution and an expansion in the range and magnitude of variability.

3.3 Effects of Bank Erosion and Its Spatial Variance in a Network

Bank erosion recruits trees to channels at rates that depend on erodibility of banks and flood frequency and magnitude (Keller and Swanson, 1979; Murphy and Koski, 1989). Erosion of streambanks depends on many factors, including particle size of the bank material (including clay) and reinforcement by roots (Hooke, 1980). Bank erosion is typically greatest in lower, actively migrating portions of channel networks and least in upper networks where banks may be comprised of bedrock, or boulders and cobbles. However, bank erosion may also result when flow is diverted around debris jams which can occur anywhere in a channel network. Although bank erosion is typically linked to flooding (Wolman, 1959), pulses of sediment or sediment waves can increase channel meandering and braiding thereby accelerating bank erosion and recruitment of trees to streams (Benda et al., 1998).

When trees are undercut by bank erosion, they tend to fall toward the channel, and the proportion of their lengths that enter a channel (P in Equation 3) can approach 100%, particularly in wide channels (Murphy and Koski, 1989). Wood recruitment from bank erosion is governed by the rate of bank retreat and the standing biomass, which in turn is a function of stand age, or time since last disturbance. A simple expression of this process is

$$I_{WB}(t) = B(t) * E(t) * 10^{-2} \qquad (7)$$

where $I_{WB}(t)$ is the annual volume of wood recruitment by bank erosion (v.u / 100 m / yr) for any segment in year t and E is the bank erosion rate (m / yr). The proportion of stem length that can enter a channel is assumed to be 100% in this analysis and so (P) is excluded from equation 8. Bank erosion is assumed to occur along only one side of a channel with bank accretion occurring on the opposite to maintain a constant channel width over time. Tree height affects the rate of influx from stand mortality (Equation 3), but not the rate of recruitment from bank erosion. Hence, the relative importance of bank erosion is greater in stands of shorter trees (Figure 8). In addition, the rate of bank erosion defines the relative importance of tree recruitment from stand mortality (Figure 8). For example, a one centimeter per year bank erosion rate, indicative of steep mountain channels (Lehre, 1978), accounts for only 14% of wood recruitment (e.g., 86% of wood recruitment is from stand mortality). In contrast, less than one half the wood storage originates from mortality when bank erosion exceeds about 6 cm per year.

To examine how the structure of variability in wood loading is affected by the rate of bank erosion, a range of erosion rates that might be encountered in a large watershed is evaluated. Bank erosion of one centimeter per year, representing armored and steep mountain channels, is contrasted against a rate of one meter per year, representing meandering alluvial channels. At the low bank erosion rate, wood loading is dominated by stand mortality and punctuated inputs from episodic fires (Figure 9). In such environments,

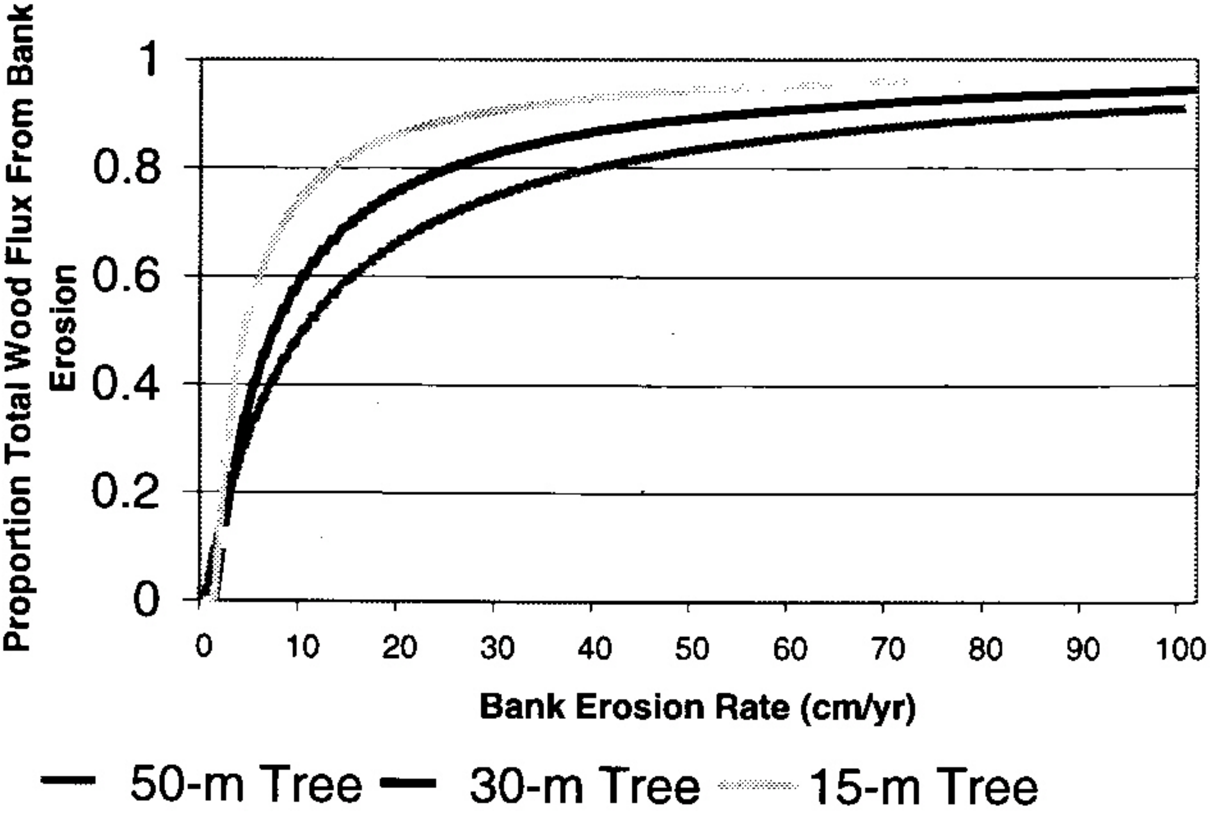


Figure 8. Proportion of total wood flux to a stream from bank erosion compared to stand mortality. Stand mortality is calculated using a 0.5% annual mortality rate and a 10% fractional proportion of trees entering a channel. Bank erosion occurs only on one side of the hypothetical stream to maintain channel width in long-term steady state. A low bank erosion rate of 1 cm yr^{-1} recruits about 15% of the total wood, while a 6 cm yr^{-1} rate is needed to dominate wood loading (i.e., greater than 50%).

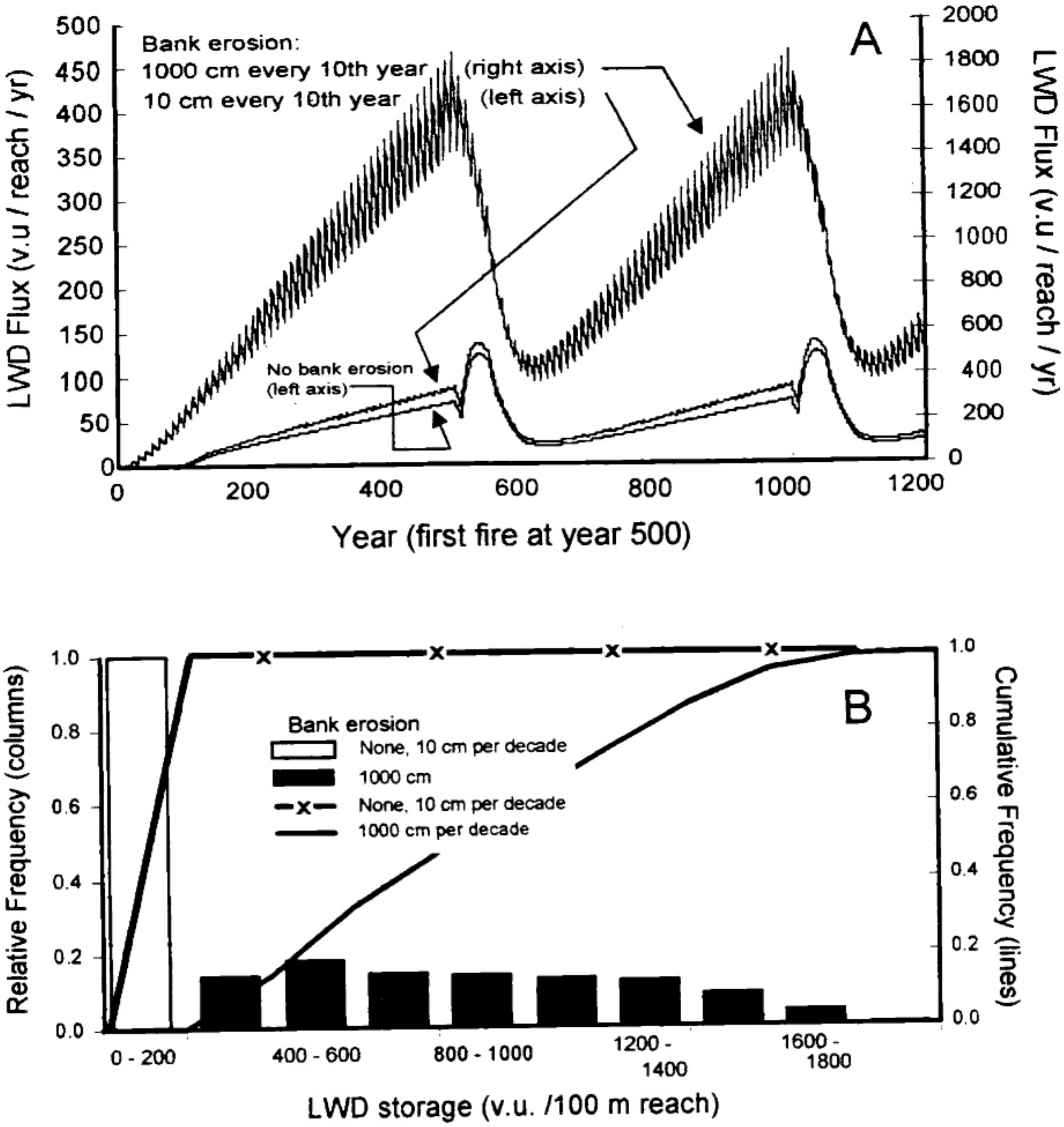


Figure 9. (A) Effect of two different bank erosion rates on storage of large woody debris for the 500 year fire cycle. A low bank erosion rate of 1 cm yr^{-1}, indicative of steep mountain channels, is almost indistinguishable from the case of no bank erosion (none) and maintains the strongly skewed distribution of wood storage in (B). In contrast, the high rate of 100 cm yr^{-1}, 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. The high frequency variation in storage (A) is the result of erosion occurring once every 10 years to mimic infrequent large floods.

wood recruitment and storage may be relatively low in the absence of other disturbances, such as fires, landslides, or wind. In contrast, the higher bank erosion rate of 1.0 m / yr dominates wood recruitment and is represented by an almost a uniform distribution of wood storage, thereby de-emphasizing effects of episodic disturbances, such as fires (Figure 9).

Increasing erosion rates downstream should result in a continual extension of the right tail of the distribution into the larger values of storage and a concomitant reduction in the probability of occurrence of lower values located in the left tail. In other words, the importance of wood recruitment by stand mortality should decrease downstream in a network in proportion to the rate of increase in bank erosion. However, wood transport also increases with increasing distance downstream and will affect the shapes of distributions of wood storage (a topic covered later). In braided channels, high rates of bank erosion may maintain riparian forests in young age classes (i.e., because of frequent disturbances), which would decrease the volume of wood from that shown in Figure 9.

3.4 Role of Mass Wasting in Wood Recruitment

Shallow and deep-seated landslides and debris flows recruit large woody debris to channels and valley floors (Swanson and Lienkaemper, 1978; Keller and Swanson, 1979; Reeves et al., 1995). The importance of wood delivery by mass wasting (I_{WL} (k,t) in (1)) depends on many factors, including the type and size of the landslide, the age of the forest (e.g., rooting strength and size of trees), the number of landslide source areas intersecting a channel reach of a given length, and the temporal frequency of landsliding. Furthermore, debris flows, and other types of landslides, deposit at least partially on fans and terraces at the base of hillslopes reducing the amount of wood delivered to a channel (Swanson and Lienkaemper, 1978; Benda, 1990).

To examine the contribution of mass wasting on wood loading, we limit our analysis to debris flows in steep, headwater channels, which is an important process in many Pacific Northwest landscapes and is relatively well defined. Debris flows can be an important wood input process because they episodically scour the long-accumulated woody debris (and sediment) from low-order to higher-order channels and valley floors. Shallow landsliding in steep, unchanneled convergent areas, called bedrock hollows, commonly initiate debris flows in first- and second-order channels (Dietrich and Dunne, 1978; Benda and Dunne, 1987). Frequency of failures in a bedrock hollow is controlled by soil production rates (e.g., soil thickening) and the rainstorm and fire climate (Dunne, 1991), and has been estimated to range between 500 and 4000 years based on radiocarbon dating and simulation modeling (Benda and Dunne, 1997; Benda et al., 1998). As a consequence, frequency of debris flows in first- and second-order channels has been estimated to range between 600 and 300 years, respectively, driven by landslide frequency and the geometry of low-order basins (Benda and Dunne, 1997; Swanson et al., 1982). In a natural setting, concentrated shallow landsliding and debris flows can occur under mature forests during large rainstorms (Benda et al., 1998;

Figure 11.1), following major fires that reduce rooting strength (Benda and Dunne, 1997; Figure 3), and can also occur in managed forests (Swanson et al., 1977).

Although debris flows and their transport of wood can be a complicated process, we simplify the problem by examining how the frequency of debris flows and their spatial distribution in a network constrains their role in the wood budget. Because first- and second-order channels comprise about 80% of the cumulative channel length in a typical mountain network (Figure 10), therefore, on average, every one kilometer of alluvial high-order channel has four kilometers of debris flow-prone tributary low-order channels. In keeping with our strategy of evaluating simple cases, this network geometry can be represented by a single high-order (i.e., greater than third-order) channel segment of length (L) having 4L of tributary channels (Figure 10). If all 5 segments are assumed to have experienced the same history of fires, then it follows that the contribution of wood by debris flows into the third- and higher-order channel segment is the ratio of the combined length of debris flow channels to the length of the receiving channel (4:1). Hence, on average over long time periods, debris flows increase wood loading in the higher-order segment by a factor of 4, assuming that debris flows transport all of the wood along scour paths, a common observation in the region (Benda, 1990).

Debris flows occurring at an average frequency of 500 years concurrently with fires (the two processes linked in time due to loss of rooting strength, Benda and Dunne, 1997; Figure 3) allows analysis of their effects in the context of patterns of wood influx and storage from mortality and fires shown in Figure 7. Because of the large store of wood that accumulates in first- and second-order channels over 500 years (wood is assumed not to be transported by streamflow in these channels because of narrow widths), debris flows yield the single largest point source of wood to high-order channels, even larger than post-fire influx of dead trees (Figure 11,A). However, wood loss by decay limits the effect of wood transported into a segment by debris flows to a short time relative to the average frequency of debris flows. For example, a decay rate of 3% yields an 80% loss of wood after approximately 60 years (Figure 5), a pattern similar to the decline of wood storage after fires. The long time between debris flows (multiple centuries) compared to the short lifespan of the deposited wood (multiple decades) limits the influence of debris flows in the total wood mass balance. The frequency distribution derived from the hypothetical time series (Figure 11,B) indicates that very large volumes of wood deposited by debris flows occur infrequently, and that the overall contribution by debris flow is limited to about 10-15% of the overall wood budget. The effect of infrequent debris flows on the structure of variability in wood storage is to shift the far right-hand tail of the distribution of storage into the higher values (Figure 11,B).

Although mass wasting that occurs infrequently may play a relatively minor role in the long-term wood budget, wood from debris flows can overwhelm all other sources to a channel or valley floor locally in time and space, and therefore dominate in the shorter-term (decadal - human lifespan). If debris flow frequency increased or wood decay decreased (for example, because of burial of wood in soil or submergence), then the relative contribution of debris flows in the wood mass balance would increase.

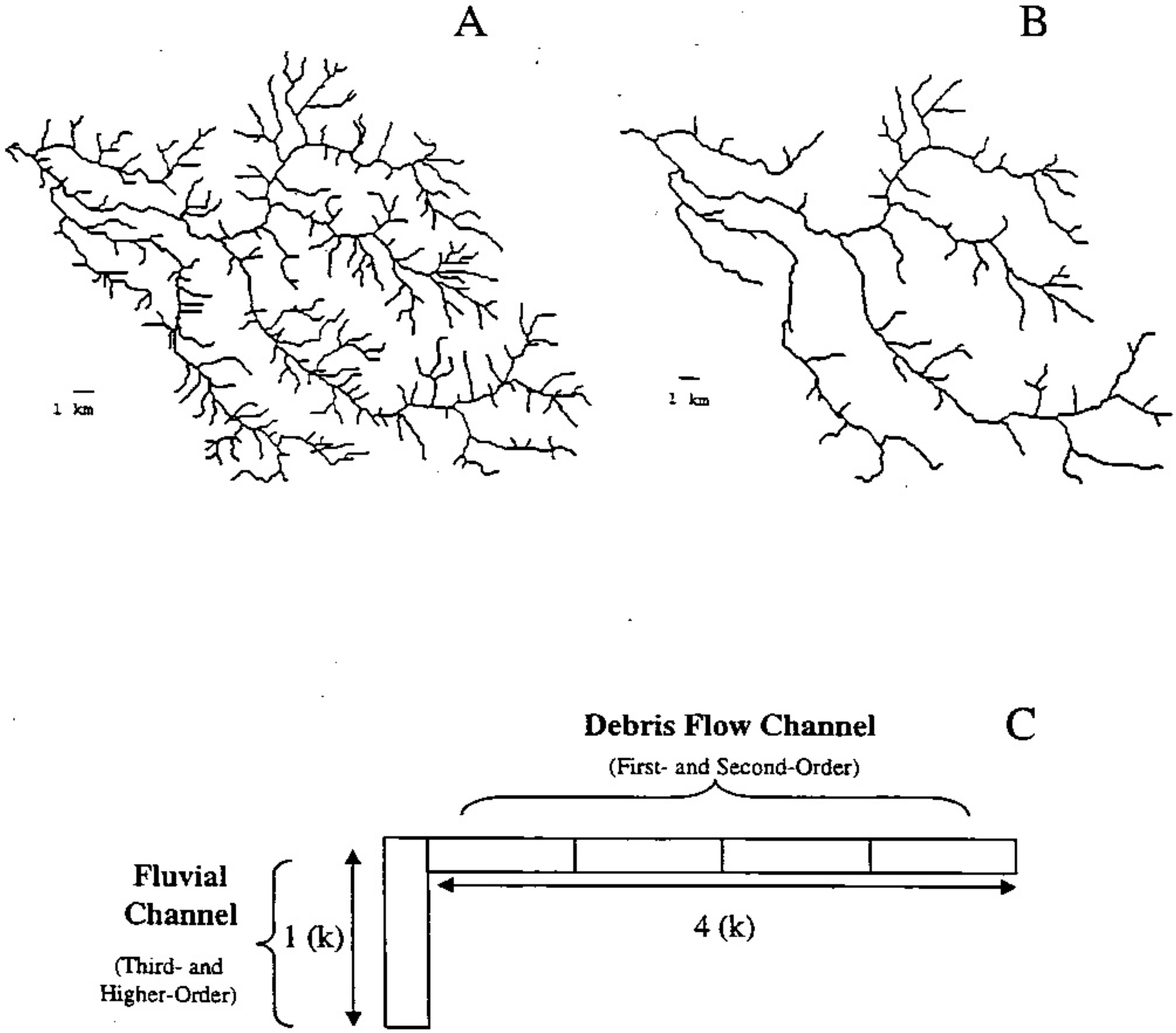


Figure 10. (A) A channel network of first- through higher-order channels. (B) The same channel network showing only third- and higher-order channels which comprise only about 20% of the total network shown in (A). (C) To estimate the role of debris flows in first- and second-order channels in the transport of wood, each third- and higher-order channel segment has, on average, four intersecting (or contributing) debris flow-prone first- and second-order channel segments.

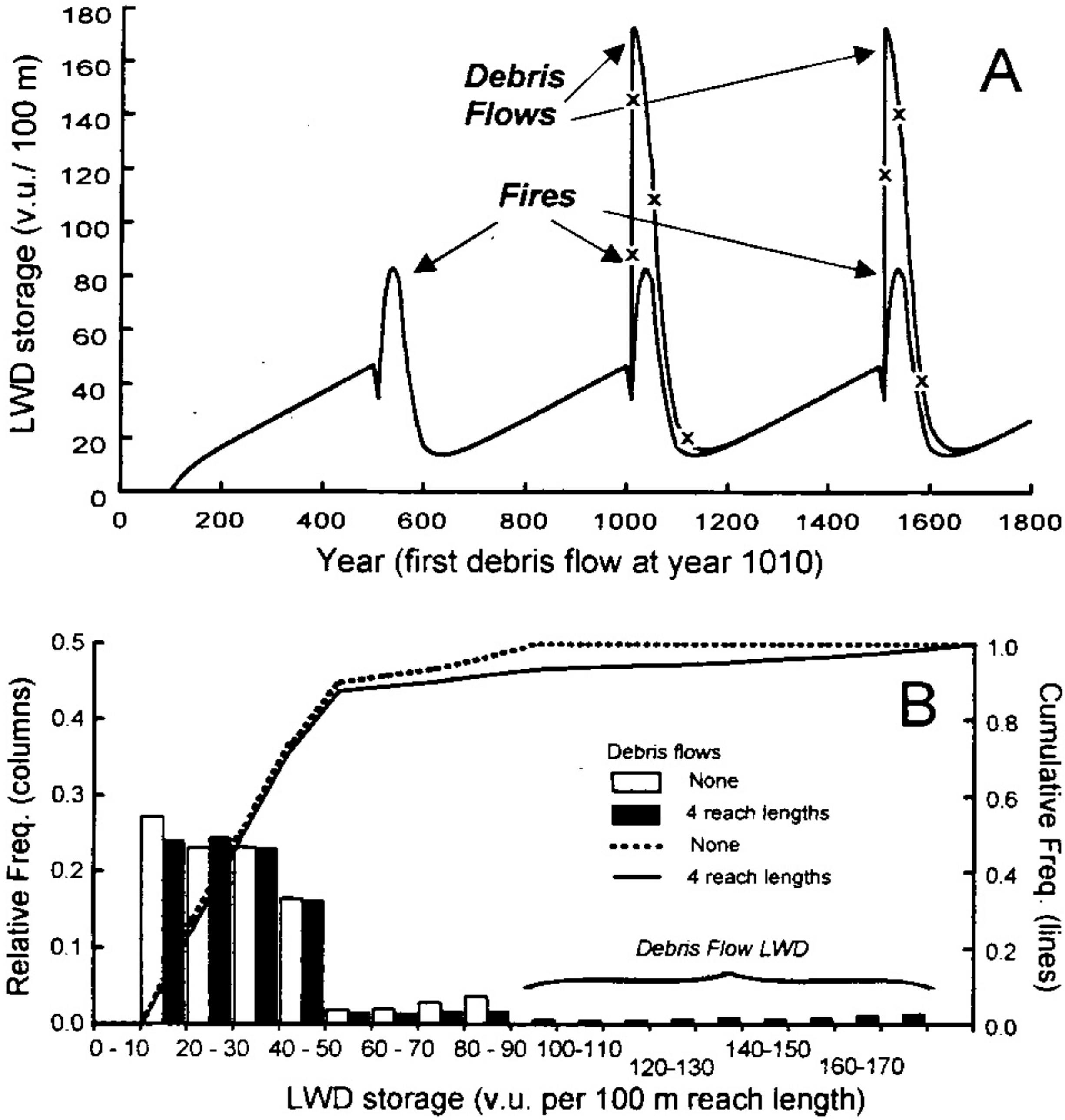


Figure 11. Effect of debris flows from first- and second-order channels occurring every 500 years. Ratio of debris flow-prone channels to alluvial channels, based on network topology in the region, is 4:1 (e.g., Figure 10). Under the condition that each channel segment in the entire network contains the same volume of wood in storage in any year (see text), on average over long time periods, debris flows increase wood loading in higher-order segments by a factor of 4. 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 (average 500 years). However, debris flows represent the single largest point loading of wood, extending wood loading to the right side of the distribution. Note the small differences in the cumulative distributions (lines in B).

There are numerous other types of mass wasting processes having different frequencies of occurrence and spatial distributions. Increasing frequency of occurrence and/or the spatial density of mass wasting may yield a larger contribution of wood to the longer-term mass balance. For example, landslides in inner gorges or snow avalanches in certain terrains can be more spatially pervasive or temporally frequent and wood delivered by these processes may be more important. Finally, wood loading to channels and valley floors by debris flow may be relatively high in landscapes with high rates of disturbance, such as in timber harvest areas.

3.5 Riparian Controls on Number of Pieces of Wood in Streams

Field studies of wood in streams commonly report wood storage in terms of number of pieces per unit channel length or piece frequency. To compare the theoretical predictions of wood storage associated with stand mortality, fires, bank erosion, and debris flows (Figures 7 through 11) with field-measured values of wood storage, we present these predictions in number of pieces per 100 m reach.

3.5.1 Converting Variable Wood Storage to Variable Piece Frequency

Piece frequency is calculated here by dividing predicted storage of wood in channels by the amount of wood that would be contained in each piece of woody debris. Both of these are quantities which vary with time. We have already shown how storage of wood is governed by recruitment rate (set by the rates of growth and mortality, fall geometry, bank erosion, landsliding, etc.) and the rate of decay. This defines the amount of wood stored in relation to standing biomass.

Piece frequency depends on the relationship between the volume of wood stored in a stream ($V_W(t)$) compared against the volume of wood contained in individual pieces:

$$P_F(t) = V_W(t) / (\text{v.u./piece}) * (100 / L) \tag{8}$$

where P_F is piece frequency (in year t) in units of number of pieces per 100 m channel length. Piece size V_P (v.u. per piece) is calculated as:

$$V_P(t) = [B(t)/ \text{S.D.}(t)] / [L_P(t) / H(t)] \tag{9}$$

where S.D. is stem density (stems/hectare) and L_P is the estimated piece length.

According to Equation 9, piece frequency increases with increasing rate of recruitment or a decreasing decay rate. The former can manifest as increases in the proportion of trees that fall into a channel or a higher mortality rate. Additional recruitment processes, such as bank erosion and landsliding, will also yield larger volumes of wood and hence, number of pieces. Piece frequency also increases when stand density increases (decreasing tree height or increasing piece length may cancel this effect). Conversely, piece frequency decreases when recruitment decreases or if decay increases. There should also be a reduction in piece frequency when stand density decreases (increasing tree height or decreasing piece length may cancel this effect).

Again, the variation in piece numbers over time can be a complicated problem by invoking all of the complexities inherent in stand growth, tree height, breakage patterns, etc. We simplify the problem by using, irrespective of stand age, constant values for stand density, tree height, and piece length representative of mature forest, although we vary biomass over time. Densities of trees in older west-side Pacific Northwest forests commonly range between 200 to 400 stems per hectare (McArdle et al., 1961; Lienkaemper and Swanson, 1987). Although stand density likely varies over time and between regions, a stand density of 250 stems per hectare is used in this analysis to represent a mature forest. Field measurements of wood in 8 to 10 m wide streams adjacent to mature forests indicates 8 m as a reasonable value to use for average piece length (L_P), independent of stand age (Bilby and Ward, 1989; Veldhuisen, 1990; Robison and Beschta, 1990). Hence, a 45 m-tall tree is equivalent to 5.6 pieces of eight-meter-long woody debris. Changing forest biomass over time results in an increasing amount of volume per piece of wood (V_P), given that stand density and piece length are assumed to remain constant after year 100 (recall that recruitment is not considered before year 100). For example, each 8 m piece of large woody debris contains 0.7 volume units at year 100 and 3.5 v.u. at year 500 (i.e., [5000 v.u. ha$^{-1]}$] / [250 trees ha^{-1}] / [5.6 pieces/tree] = 3.5 v.u./piece). This is equivalent to smaller diameter woody debris in young forests and larger diameter pieces in older forests.

Time series of wood storage expressed in terms of piece frequency are shown in Figure 12 for three cases: (1) A 500-year fire cycle and associated stand mortality; (2) fires, mortality, and debris flows (every 500 years); and (3) fires, mortality, and 1 cm yr^{-1} bank erosion. Number of pieces of wood per 100 m segment of channel ranges from less than 10 in young forests with no bank erosion to a high of 70 following fires and debris flows. Fires and mortality alone yield a relatively constant 20 pieces per 100 m over most of the cycle, a consequence of storage and piece volume increasing at similar rates such that their ratio remains almost constant. A low bank erosion rate of 1 cm yr^{-1}, in addition to fires and mortality, increases the piece frequency to approximately 25 per 100 m except during periods following fires. The long-term mean piece frequencies for the three different cases are respectively 20, 24, and 25 pieces per 100 m.

3.5.2 Corroboration: Variation in Piece Frequency Compared to Field Measurements

Despite the simplifications employed in estimating variability in wood storage over time and in our calculations of piece frequency, predictions (Figure 12) are similar to field measured values. Bilby and Ward (1989) measured a range of 10 to 60 pieces (average of 24) of woody debris per 100 m in channels between 4 and 20 m wide in unmanaged watersheds in southwest Washington. In unmanaged watersheds in southeast Alaska, Robison and Beschta (1990) measured a range of piece frequencies of 25 to 42 per 100 m for streams between 4 and 13 m wide. Six other studies in unmanaged watersheds, summarized by

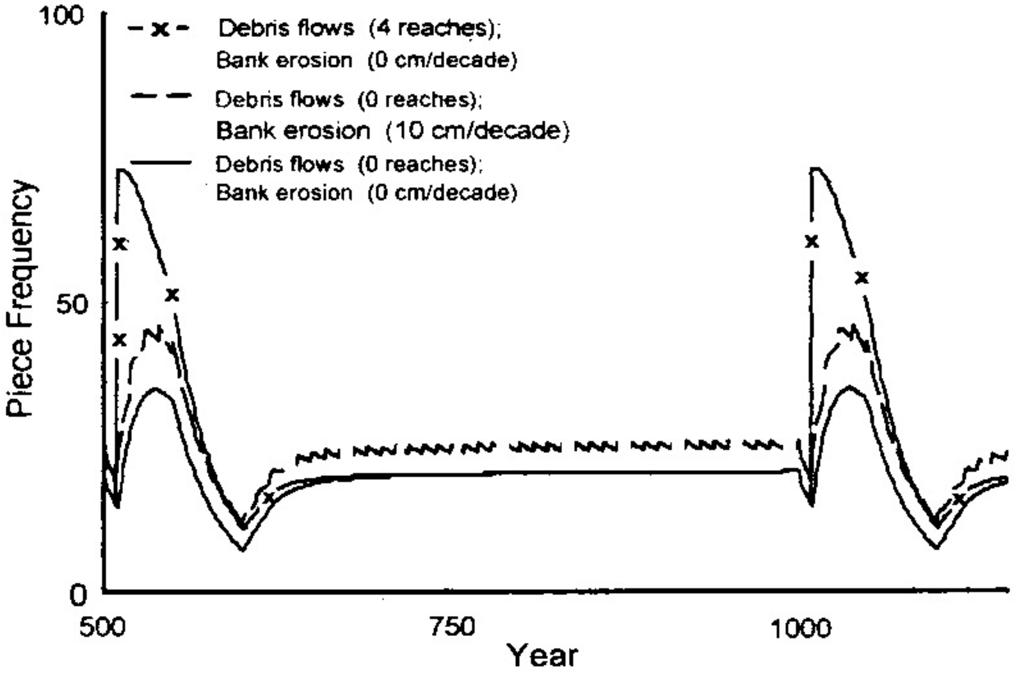


Figure 12. Frequency of pieces of large woody debris per 100 m channel segment that represents three cases: 1) Chronic stand mortality and fires; 2) fires, mortality, and 1 cm yr^{-1} bank erosion; and 3) fires, mortality, and debris flows every 500 years. An annual decay rate of 3% is used and stream transport of wood is not included. Fires and mortality alone yield a relatively constant 20 pieces / 100 m over most of the cycle, a consequence of storage and piece volume increasing at similar rates such that their ratio remains almost constant. Fires and debris flows increase piece frequencies to 30 and 70, respectively. The addition of debris flows increases the mean piece frequency from 20 to 24. Predicted piece frequencies are similar to several field studies which measured piece frequencies in Washington and Alaskan streams of between 4 and 70, with many values around 20 to 30.

Peterson et al. (1992), revealed values between 11 and 60 pieces per 100 m (average about 40) in streams 4 to 20 m wide. The similarly between the predicted range of piece frequencies and field measurements indicate that our simplified (coarse grained) analyses of wood storage and piece frequencies are sufficient to reproduce values of wood loading that occur in nature. This is a consequence of two factors inherent in our approach. First, the use of relatively narrow ranges of landscape process rates (fire cycles, bank erosion, debris flows, decay rates etc.) that occur in nature constrains the relative range and magnitude of variation in wood flux and storage, even using arbitrary volume units (any value of biomass units could have been used in this analysis). This establishes the correct spread (or range) of piece frequencies (e.g., range over about a factor of 3 to 7 (not including the effect of fluvial transport). Secondly, the relatively narrow range of stand density, piece breakage (in the form of average piece length), tree heights, and geometry of random tree fall) found in nature, which ultimately restricts how many pieces will be introduced to a channel from a streamside forest (in a non transport case), constrains the absolute magnitude of piece frequencies. Hence, both the range and also the absolute magnitude of piece frequencies predicted by our simplified approach accord with field measurements.

Information on stand density and piece size from Montana is used to illustrate how changing several of the variables in Equations 8 and 9 can affect piece frequency. Streamside forests in the more mesic environments of Montana have a fire frequency of approximately 150 - 200 years, a stand density of approximately 100 trees per hectare, and an average length of large woody debris in streams of 6 m (unpublished data, personal communication, Jeff Light, Plum Creek Corporation). From Equations 8 and 9, more frequent fires should lead to lower standing biomass and hence smaller pieces. Furthermore, a smaller stand density should yield a lower piece frequency, although a shorter average piece length may counteract this effect. Using the field data from Montana, the volume per piece at year 150 (calculated as described above for west-side forests) is 3 indicating that piece diameter (and volume) is less in the drier forests of Montana. The reduction in stand density, tree height, and piece length (keeping all other factors the same as west-side forests) yields a piece frequency of 5 per 100 meters, approximately one third the wood loading compared to mature west-side forests. Field data will be needed to test the hypothesis of decreasing piece frequency in more mesic forests.

3.6 Fluvial Transport of Wood and Loss to Valley Floor Storage

In the preceding analyses of the inputs of woody debris (by stand mortality, post-fire pulses, bank erosion, and debris flows), stream transport was not considered in order to reduce complexity and to represent those channels where stream transport is a minor process (Figures 7 – 12). Transport of wood by streams and rivers should alter the shapes of the distributions of storage (in terms of volume or piece frequency) depending on the number of upstream contributing segments and whether wood is lost from the system, either through export or through transfer to valley floor storage.

3.6.1 Factors Governing Wood Transport

Several factors important in wood transport have been identified in empirical studies. Transport of wood by stream flow depends on piece length, and, in general, highly mobile pieces are shorter than the width of the channel at bankfull (Lienkaemper and Swanson, 1986; Nakamura and Swanson, 1993). Since channel width increases downstream, an increasing proportion of all wood becomes mobile (Bilby and Ward, 1989). In addition, as discharge increases, total stream power also increases (Richards, 1982), although irregularly downstream because of variation in channel slope and abrupt increases in drainage area at tributary confluences. Channels of increasing stream power should be able to transport organic debris more efficiently because flow energy (in terms of depth and velocity) is needed to counter the effect of wood deposition along rough channels and their margins. Hence, there should be a progressive increase in wood transport downstream and therefore an increasing distance between channel-spanning (e.g., non mobile) pieces downstream (Likens and Bilby, 1982).

Under the condition that piece length is shorter than bankfull width for significant transport to take place, piece length limits the portion of the network where wood transport by fluvial processes is an important process (Keller and Swanson, 1978). The average piece length of in-stream woody debris in the Pacific Northwest has been measured to be about 8 m (Veldhuisen, 1990; Robison and Beschta, 1990; Bibly and Ward, 1989). First- and second-order channels generally have width less than 7 m wide (Swanson et al., 1982; Benda, 1988; O'Connor, 1993). Therefore, first- and second-order channels would exhibit the wood recruitment and storage patterns illustrated in Figures 7 – 12 (i.e. where transport is a minor process), with the exception that in some channels (of the appropriate steepness) debris flows would occasionally scour all of the long-accumulated wood (and sediment), resetting wood storage to zero. Since first- and second-order channels can comprise 80% of a channel network (Swanson et al., 1982; Benda, 1988), significant wood transport by fluvial processes may be limited to approximately 20% of channel length in a watershed.

3.6.2 Role of Wood Transport in Generating Variability

Fluvial transport of wood is a complicated problem and we are not aware of physically-based models of transport. In keeping with our coarse-grained strategy, we devised a scheme for evaluating the effect of transport on wood storage based on (1) a transport rule where influx and efflux occur independently; (2) all wood stored in a segment becomes mobile during transport events (mimicking breakup of all transport-impeding jams) and 100% of mobile wood becomes captured in segments where wood is not mobile (representing an environment of many jams); and (3) the use of a simple river channel comprised of some number (Nc_{MAX}) of 100-meter long segments with no intervening tributaries. This approach allows us to examine two consequences of wood transport: (i) Variability in wood supply (in a single storage reach, such as one containing jams) that would arise from varying the number of upstream contributing segments, and (ii) the progressive change in wood supply downstream.

Year-to-year variability in flood magnitude will result in the number of upstream contributing segments (Nc(t)) to vary from year to year. Nc(t), and the time between transport events, are treated as random variables to mimic an interannual variability in annual maximum flood magnitude at a location (with Nc(t) being zero except in years randomly determined to be transport years). In the analysis of variability of wood storage, the number of contributing segments (Nc(t)) is randomly selected from 1 to a maximum number of upstream segments (Nc_{MAX}) each time an influx event is simulated. In the following illustrative example, fluvial transport events in a river channel comprised of five 100 m-long segments (i.e., Nc_{MAX} equals 5, and the length of the river channel is 600 m) occur stochastically at an annual probability of 0.03 or, on average, 3 times per century. Such a frequency of log jam failure is consistent with field measurements in which log jams ages were found to be on the order of several decades (Hyatt, 1998). The volume of wood liberated from each contributing segment - assumed to be the same in each segment - is an annually random variable, with the value obtained by sampling the time series shown in Figure 7, representing wood storage from chronic mortality and fire pulses for the 500 year fire cycle. The results of the stochastic simulations are shown in Figure 13 against the non-transport case, for reference.

The cases of influx only, export only, and combined influx and export were examined. In all cases, fluvial transport created significant variability in wood storage compared against the non transport case. Even with only five 100 m-long segments contributing (transport events involved between 1 and 5 segments) wood storage varies by a factor of 10 to 30, either when jams break and wood is transported (Figure 13,A) or when jams form and all wood is captured (Figure 13,B). Fluvial import of wood only may reflect behavior associated with persistent and large log jams in large rivers (Sedell and Froggatt, 1984) or jams that occur at abrupt constrictions, such as mouths of canyons. Fluvial export of wood only may be indicative of steep, high energy streams confined between hillslopes or located in canyons where little wood may be held and volumes would be chronically low. The more common condition of influx and export (Figure 13,C) likely characterizes most channel networks where wood transport occurs. When jams form, wood storage can abruptly increase by hundreds to thousands of percent (depending on the number of contributing channel segments during any event) and likewise similar magnitude losses of wood can occur during large floods when whole reaches may be swept clean of woody debris. A similar analysis to that of Figure 13,C with the addition of processes active in real watersheds, including debris flows and bank erosion, is represented in piece frequencies for illustration (Figure 14,A). Transport (from 1 to 5 upstream contributing segments) caused piece frequencies to range from zero (representing collapse of jams) to over 200 pieces (in jams); compare this to the range of 20 to 70 in the non-transport case in Figure 12. The majority of values lie between 10 and 50, again similar to field measured values (Section 3.5.2).

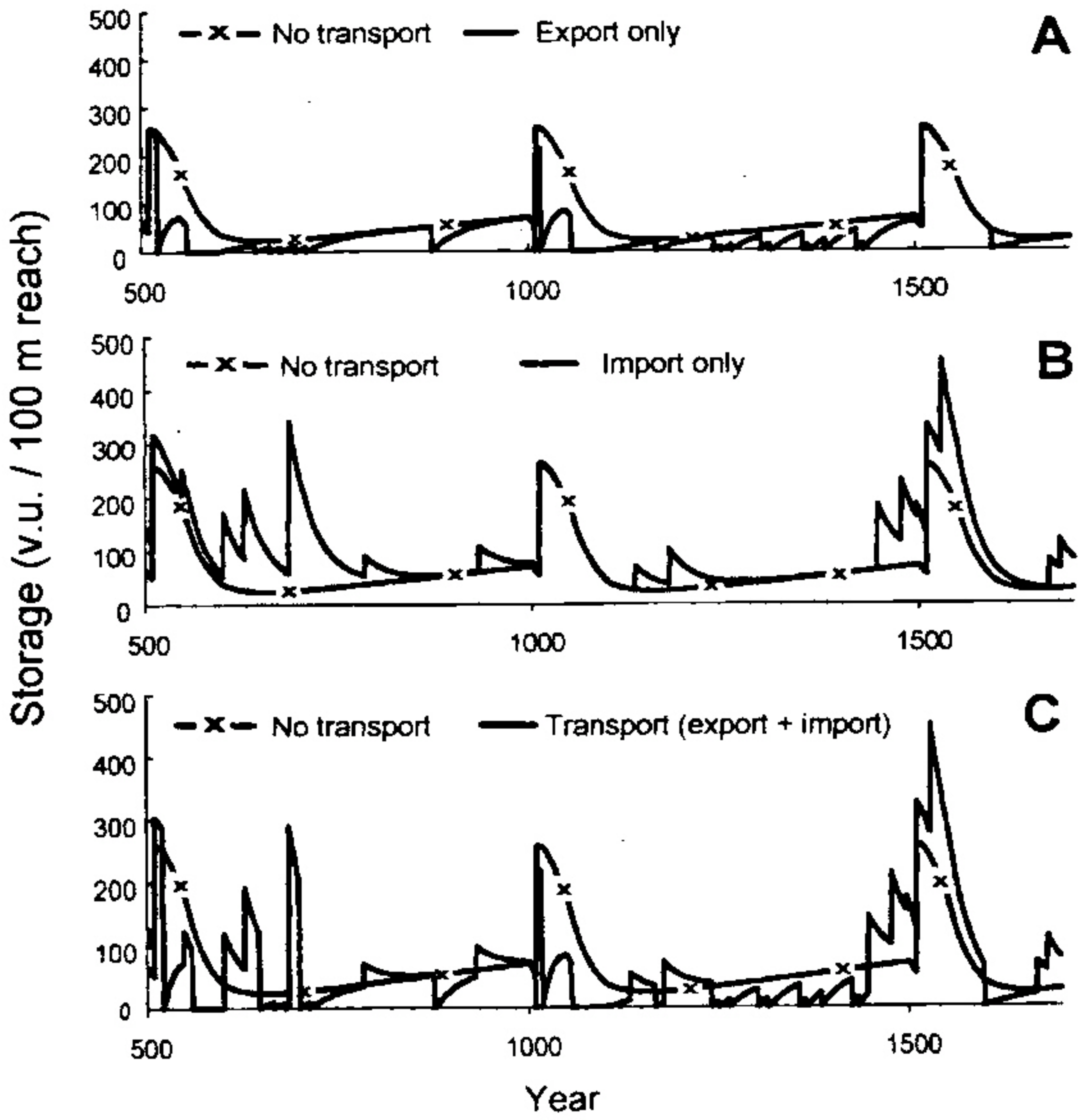


Figure 13. An illustration of the effect of stream transport of wood from a maximum of five 100 m-long contributing segments to a downstream segment (number of contributing segments (1-5) vary over time). The wood loading characteristics represent the 500-year fire cycle and a decay rate of 3% (Figure 7). Influx and export events occur stochastically but on an average of 3 times per century. Three cases are shown: (A) export only; (B) influx only; and (C) a combination of export and influx. The no transport case is shown for comparison. In all cases, fluvial transport increases variability in wood storage by up to a factor of 20 to 30, either when jams break and wood is transported (A) or when jams form and all wood is captured (B). The more common condition of influx and export (lower) shows that wood storage can commonly go to zero but more consequential is the much larger relative increases in storage due to the five upstream contributing segments.

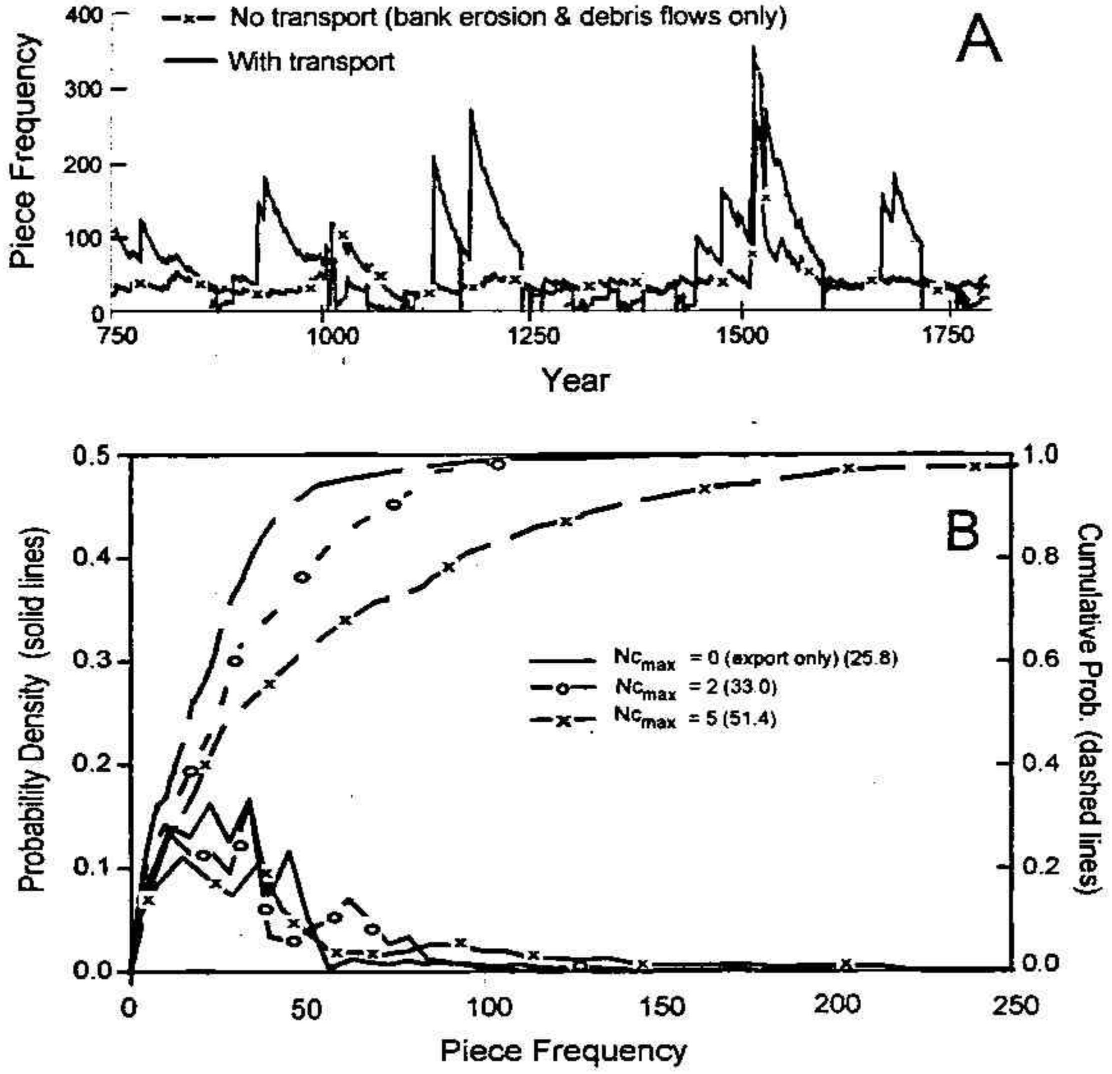


Figure 14. (A) A similar analysis to that of Figure 13 with the addition of processes active in real watersheds, including debris flows and bank erosion. Results are represented in piece frequencies. Transport (from 1 to 5 upstream contributing segments) caused piece frequencies to range from zero (representing collapse of jams) to over 200 pieces (in jams). The majority of values lie between 10 and 50, similar to field measured values. (B) The effect upon the piece frequency distribution of increasing the number of upstream contributing reaches from 0 (no-transport case) to 2 to 5 is a progressive transformation of the distribution. In the absence of wood transport, the distribution is approximately log normal having a mean of 26 pieces per 100 m . Wood transport shifts the distribution both towards the left side (i.e., lower piece frequencies) when jams fail and wood is transported, and towards the right (i.e., higher piece frequencies) when jams form and wood is captured (originating from upstream reaches). In the absence of loss of wood to stream export or abandonment on terraces or floodplains, wood supply is predicted to quickly increase downstream. However, the channel length over which increases can occur could be limited by decay or valley floor storage of wood and should reach some maximum.

3.6.3 Role of Wood Transport and Valley Storage in Changing Wood Abundance

To examine the effect of moving downstream in a network on wood storage requires that the maximum number of upstream contributing segments (Nc_{MAX}) be incrementally increased. Similar to the analysis in Figure 14,A, wood storage includes debris flows and bank erosion, in addition to chronic mortality and fire-pulsed wood. The effect upon the piece frequency distribution of increasing the number of upstream contributing reaches from 0 (no-transport case) to 2 to 5 is a progressive transformation of the distribution of storage. In the absence of wood transport, the distribution is approximately log normal having a mean of 26 pieces per 100 m (Figure 14,B). Wood transport within an individual segment shifts the distribution both towards the left side (i.e., lower piece frequencies) when jams fail and wood is transported, and towards the right (i.e., higher piece frequencies) when jams form and wood is captured (originating from upstream reaches). Such expansion of the distribution reflects an increase in the range and magnitude of variation in wood storage.

The increasing supply of mobile wood as one moves downstream (that is, as Nc_{MAX} is increased in our analysis) is reflected in a progressive shift in the cumulative distribution plot of piece frequency (Figure 14,B), indicating the occurrence of larger volumes of wood an increasing proportion of the time. This pattern is also reflected in an increase in the mean piece frequency with increasing distance downstream. The channel length over which increases can occur, however, could be limited by decay or valley floor storage of wood and should reach some maximum (Figure 15,A). When jams do not fail or when jams are abandoned on floodplains, transport would be limited to the channel length between jams and downstream increases in wood flux and storage should not occur. Either increasing probability of jam failure or higher rates of wood abandonment on floodplains and terraces downstream should result in a decreasing storage of wood (Figure 15,A). Field measurements could be used to evaluate these hypothetical patterns of in-stream wood storage. Bilby and Ward (1989) documented a decreasing piece frequency with increasing channel width. In contrast, Beechie and Sibley (1997) and Martin et al. (1998) did not find a relationship between piece frequency and channel width. Because all of the field studies involved sub-sampling channel networks within numerous watersheds, they did not evaluated the spatial distribution of wood within a single river network. Measurements of wood throughout whole networks (at least in the fluvial transport zone) would be necessary to test the theoretical predictions made here. An additional complexity is that the spatial distribution of wood transporting-segments in a network may vary over time depending on the stochastic recruitment of woody debris which is dependent on time since last disturbance, including by fires, mass wasting, and floods.

Wood transport limited to channel lengths between jams should result in wood storage (at jams) that scale with the distance between jams. In streamside forests with a diversity of tree heights, the number

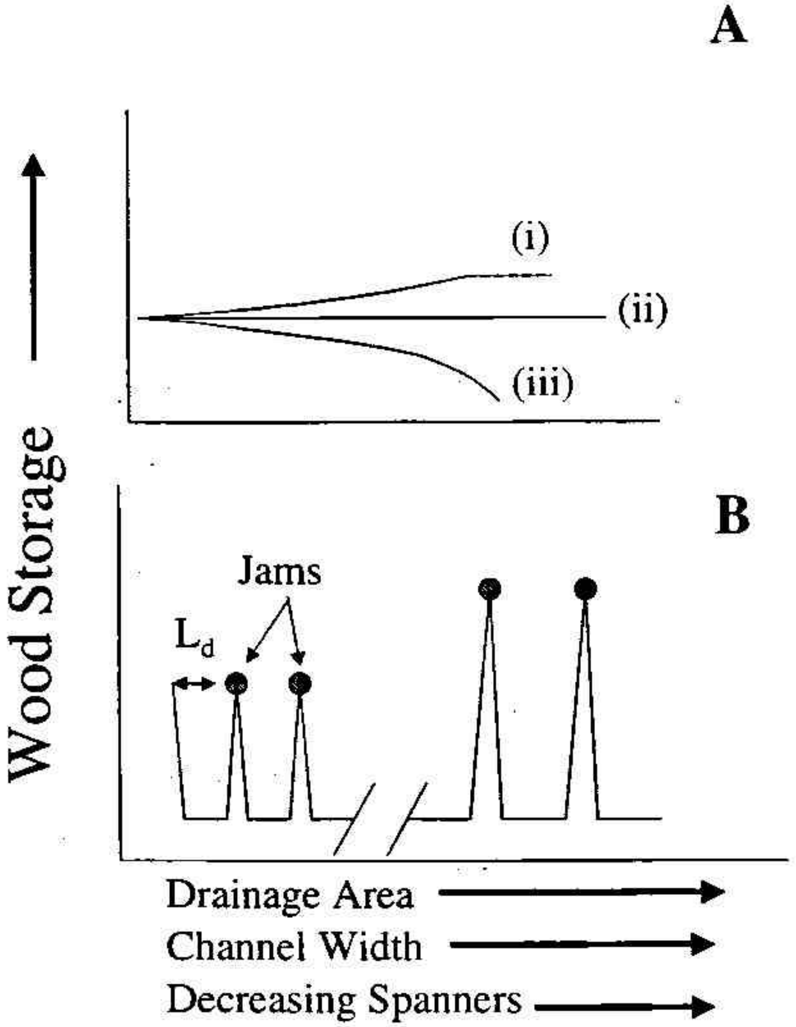


Figure 15. (A) Three different effects of wood transport on patterns of wood storage in jams. (i) Increasing the number of channel segments that can contribute mobile wood through jam failure will yield an increasing volume of wood storage in jams with increasing drainage area (or width), a condition represented in Figure 14,B. However, the channel length over which increases can occur could be limited by decay or valley floor storage of wood and should reach some maximum (illustrated by the dashed line). (ii) When jams do not fail or when jams are abandoned on floodplains transport would be limited to the channel length between jams and downstream increases should not occur. (iii) Either increasing probability of jam failure or higher rates of wood abandonment on floodplains and terraces downstream should result in decreasing storage of wood. (B) Wood transport limited to channel lengths between jams (case ii) should result in wood storage (at jams) that scale with the distance between jams (L_d). Increasing channel width and corresponding decreasing likelihood of forming jams should yield an increase in inter-jam spacing and hence an increase in the volume of wood stored in jams. An increase in the number of channel segments that can contribute mobile wood through jam failure (illustrated in A(i) and Figure 14,B) should result in additional increases in wood storage in downstream debris jams.

of trees that can span a channel should decrease with increasing channel width downstream. Increasing channel width and a corresponding decreasing likelihood of forming jams should yield an increase in inter-jam spacing and hence an increase in the volume of wood stored in jams with increasing drainage area (Figure 15,B).

During floods or high sediment supply events wood can be transferred to floodplains and newly-formed terraces (Miller and Benda, 1998). Wood can also become abandoned when a stream or river abruptly or gradually migrates around a debris jam (Triska, 1984; Kochel et al., 1987; Abbe and Montgomery, 1996). These represent losses in the wood mass balance (S_O in equation 1) which can offset increases in wood flux and may lead to a relatively constant wood storage downstream (Figure 15). Burial of wood may also decrease wood decay and increase the longevity of woody debris. Exhumation of buried wood along eroding channels has also been observed (Triska, 1984) and could be considered as an additional wood recruitment process. The effects of burial and subsequent exhumation of wood on the long-term wood mass balance has never been quantified.

Wood storage in terms of piece frequency can also be used to predict a likely rate of wood production in a watershed which might be useful for analyses of wood loading to estuaries or oceans (Gonor et al., 1988). Wood recruitment by fires, mortality, bank erosion, debris flows, and decay (Figures 14,A) translates to a wood production rate of about one piece per 100 meter segment per year. Using a drainage density in third- and higher-order channels (where wood transport is likely to occur) of 1.5 km/km^2 (Oregon Coast Range, Benda, 1994), production would be approximately 15 pieces of woody debris/km^2/yr. This wood production rate in a 100 km^2 watershed would yield approximately 1500 pieces of large woody debris per year. If wood pieces are converted to volume, using an average 50 cm diameter (for a 10 m wide channel using Bilby and Ward, 1989) and 8 m length yields about 6 cubic meters per piece and therefore wood production (or flux, if all is transported) would be about 9,000 cubic meters per year from the 100 km^2 basin. At the landscape scale for the entire 20,000 km^2 Oregon Coast Range, this would translate to 3 X 10^5 pieces or about 2 X 10^6 cubic meters of wood annually to the Pacific Ocean. However, wood storage on floodplains or its burial in terraces may reduce wood export to a small fraction of the total wood production rate.

4.0 Theoretical Principles on Wood Abundance: Practical Applications

The importance of the five landscape processes in governing woody debris recruitment and storage outlined in this study has been previously described by others (see citations throughout text). However, time limitations of field studies and the complexities of natural environments have heretofore limited the evaluation of the full range and magnitude of variability in wood abundance in streams.

Relationships among landscape process rates, their spatial variance in a basin or landscape, and the structure of variability in wood loading (in the form of frequency distributions) constitute a set of general theoretical principles. The general principles (summarized in Figure 16) reflect how narrow ranges in process rates within watersheds (such as fire cycles, landslide rates, and bank erosion etc.) constrain the range and magnitude of variability in wood recruitment and storage. Changing the magnitude of process rates or attributes of riparian forests (within an individual watershed or across different landscapes) changes the shapes of distributions, or the structure of variability, in predictable ways. For example, a lower fire frequency will shift the distribution of wood recruitment and storage to the right while a higher fire frequency will shift the distribution to the left (Figure 8), and so on with the other four processes. In essence, one uses the theoretical principles (Figures 3 to 15) to organize and systematize conceptualizations, field investigations, and predictions of wood abundance in streams, including the range of variability.

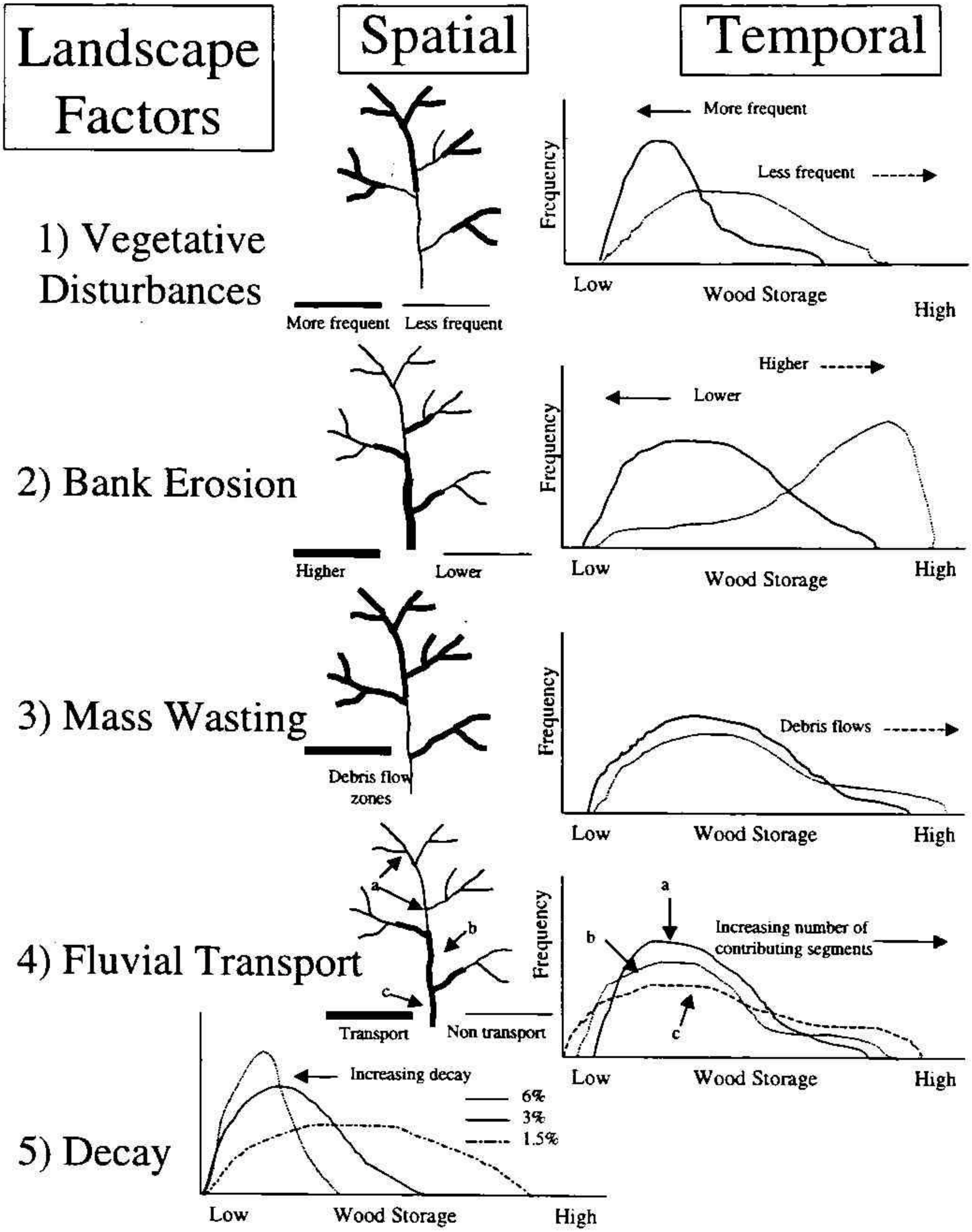
The theoretical principles have several practical applications: (1) Providing a framework for constructing wood budgets, including estimating the range and magnitude of variability; (2) generating testable hypotheses on current wood loading and future trends; and (3) setting realistic targets for wood recruitment and storage in the context of forest management.

4.1 A Framework for Constructing Wood Budgets, Including Estimating the Range and Magnitude of Variability

Environmental systems with definable inputs, outputs, and residence or storage times lend themselves to an accounting of the 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 (Dietrich and Dunne, 1978; Dunne, 1984). Constructing a sediment budget allows one to systematically account for, and make quantitative estimates of, all major physical and biological processes in a basin that produce, route, and store sediment on hillslopes and in channels (Reid and Dunne, 1996). Such an accounting procedure of sediment transfer and storage is used to explain an observed sedimentation regime in a watershed, or to make predictions about future sediment production and routing. Constructing budgets also provides a systematic way to organize one’s thoughts about a complicated environmental system, and can be used solely as a qualitative or conceptual tool for forming explanations of field conditions.

Woody debris in channels has definable inputs, outputs, and storage times, and hence, lends itself to a budgeting procedure. Solving the wood mass balance (equation 1), i.e., the wood budget, leads to an understanding of the relative importance of various landscape processes in controlling wood abundance. Constructing a wood budget requires making quantitative (or qualitative) estimates of wood recruitment from terrestrial sources (mortality, bank erosion, landsliding, etc.), wood decay (including abrasion), stream influx and efflux (by water transport and debris flows), and storage in channels, and on fans, terraces, and floodplains. Although complete wood budgets (i.e., all inputs, outputs, and storage processes and rates throughout a watershed) may be needed for certain purposes, partial wood budgets may focus more

Figure 16 – following page. The theoretical principles are comprised of the relationships among the general magnitude of landscape process rates (e.g., fire frequency, bank erosion, mass wasting frequency, decay, and transport etc.), their spatial variance in a watershed (or landscape), and the resulting shapes of the frequency distributions of wood recruitment or storage. Narrow ranges in process rates within watersheds (such as fire cycles, landslide rates, and bank erosion etc.) will constrain the structure of variability in wood recruitment and storage. Changing the magnitude of process rates or attributes of riparian forests (across different landscapes) changes the shapes of distributions, or the structure of variability (solid to dashed lines in the distributions). One uses the theoretical principles to organize and systematize inquiries or investigations of wood abundance in streams, including the range of variability. Each of the five landscape factors has a spatial context in a watershed (denoted by thick black lines in the channel network). This figure summarizes Figures 3 – 15.

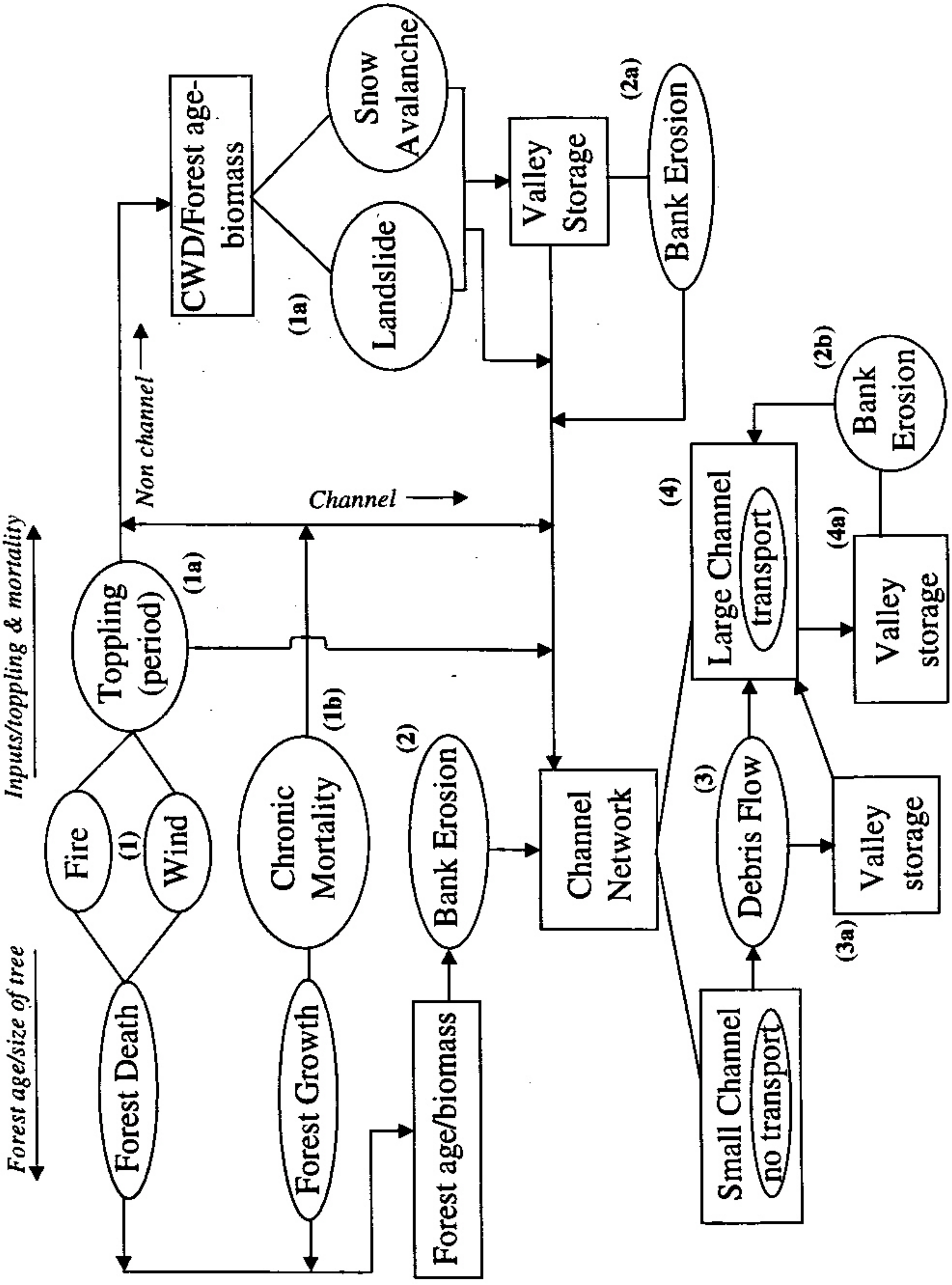

Landscape Factors
Spatial
Temporal
1) Vegetative Disturbances
More frequent
Less frequent
Frequency
More frequent
Less frequent
Low
Wood Storage
High
2) Bank Erosion
Higher
Lower
Frequency
Higher
Lower
Low
Wood Storage
High
3) Mass Wasting
Debris flow zones
Frequency
Debris flows
Low
Wood Storage
High
4) Fluvial Transport
a
b
c
Transport
Non transport
Frequency
a
b
c
Increasing number of contributing segments
Low
Wood Storage
High
5) Decay
Increasing decay
6%
3%
1.5%
Low
Wood Storage
High

narrowly on particular elements. For some applications it may be sufficient to define one or more of the following, even for a specific portion of a watershed: (1) the approximate volumes of wood contributed to channels by various recruitment processes; (2) the size distribution of the debris being delivered; (3) the stability of the debris in channels, including estimates of its residence time; (4) storage of wood on floodplains, fans, and terraces; and (5) legacy effects (increases or decreases in wood storage) from major disturbances, including fires, windstorms, landslides, etc.

Although the term ‘budget’ has not been previously used to describe studies of large woody debris fluxes into and out of channels by their authors, many studies could be considered as partial budgets. For example, Keller and Swanson (1977) developed a conceptual 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 between forest age, wood inputs, and the formation of wood jams. Field measurements of in-channel woody debris by Murphy and Koski (1989) and Martin et al. (1998) was used to define the relative contribution from stand mortality, bank erosion, and landsliding. From these data, they also estimated a wood depletion rate. Grette (1985) estimated input rates for deciduous and conifer trees in streams draining the Olympic Peninsula as well as a wood depletion rate. Dimensions (diameter and length) of stable pieces of woody debris in streams of different sizes was investigated in southwest Washington streams by Bibly and Ward (1989). All of these studies and numerous others not cited, identified components of the wood mass balance in streams, or the wood budget. However, the authors are not aware of a complete wood budget developed at the scale of an entire watershed.

Constructing a wood budget requires that all wood inputs, outputs, transport, and decay processes be considered in a systematic fashion. For either partial or complete budgets, each of the important landscape processes and storage reservoirs must be identified, either in the field or in the office. A flowchart that illustrates a wood budget is shown in Figure 17. Time limitations of field studies and complexities of natural environments can complicate development of wood budgets. In addition, since only a point in time is measured, information on the range and magnitude of variability on wood recruitment and storage may be difficult to obtain. Here is where the theoretical principles on wood abundance can come into play. Relationships between landscape process rates and shapes of distributions of wood recruitment and storage (Figure 16) can be used to develop initial hypotheses regarding wood abundance. Such hypotheses can be used to design studies, including targeting field measurements in context with obtaining appropriate information on past and present watershed conditions. Furthermore, the theoretical principles can be used as a tool to parlay limited data collected at small temporal and spatial scales into hypotheses on the range and magnitude of variability in wood recruitment and storage at the scale of landscapes.

Figure 17 – following page. Flowchart of a wood budget showing the principle wood input, output, transport, storage, and decay processes. Landscape processes are denoted by ovals and wood storage reservoirs by squares or rectangles. (1) Cycles of forest death (fire and wind) and growth affect both punctuated wood supply (via toppling and landsliding from reduced root strength (1a)) and chronic mortality (1b). (2) Bank erosion recruits trees to channels, and also exhumes wood stored on fans and terraces by landsliding (2a) and wood abandoned on valley floors (2b). (3) Debris flows transport wood stored in low-order channels to higher-order channels; a portion of that wood may be stored on valley floors and recruited later (3a). (4) Fluvial transport of wood changes wood flux and supply downstream depending on the number of upstream contributing segments and wood storage on floodplains and terraces. Decay affects storage in all reservoirs. Constructing a wood budget requires making quantitative or qualitative estimates of all the major landscape processes and storage reservoirs.


Forest age/size of tree
Inputs/toppling & mortality
Forest Death
Fire
(1)
Wind
Toppling (period)
(1a)
Non channel
Channel
CWD/Forest age-biomass
(1a)
Landslide
Snow Avalanche
Valley Storage
(2a)
Bank Erosion
Forest Growth
Chronic Mortality
(1b)
Forest age/biomass
Bank Erosion
(2)
Channel Network
Small Channel
no transport
Debris Flow
(3)
Valley storage
(3a)
Large Channel
transport
(4)
Valley storage
(4a)
Bank Erosion
(2b)

4.2 Generating Testable Hypotheses on Current and Future Wood Loading

Short-term field measurements sample only a point in time. Hence, it may be of interest to know where a particular basin resides with the theoretical range of variability For example, is it likely that short-term field measurements will be able to estimate a value of wood storage close to the long-term mean, indicating that the mean is a reasonable approximation for system behavior or a target for environmental assessments and monitoring? Or, are estimates of the variance more appropriate? Application of the theoretical frequency distributions (Figures 3 – 15), can be used to constrain the shape of the population distribution (e.g., all years) from which the empirical sample was drawn (Figure 18). To accomplish this, knowledge of basin history, in terms of fires, wind, mass wasting, and floods would be used to place the wood storage observed in any year in context with the long-term distribution, or range and magnitude of variability (e.g., what types of landscape processes and basin histories are required to access certain portions of a theoretical distribution).

Likewise, projections of future trends may be difficult if episodic processes, such as large floods, fires, or mass wasting, are key elements in the wood mass balance. Theoretical shapes of distributions (Figure 16) can be used to help constrain likely future trends, and the temporal and spatial scales over which changes might be expected to occur. In addition to information on basin history, knowledge of future watershed trends (aging forests, increased landslide potential, etc.) can be used to develop hypotheses on future conditions (P's in Figure 18).

The distributions presented in this study (Figures 3 – 15) relate to temporal behavior in a segment, although many segments within a similar environment may have similar looking distributions. Field measurements at one point in time within a network can be used to construct an empirical frequency distribution of wood storage (Figure 19). Theoretical distributions (representative of a population of segments) can then be used to generate hypotheses on future expectations, in the form of evolution in the shapes of the empirical frequency distributions over time. Future measurements in the same network could be used to test and verify the initial hypotheses. Additionally, empirical frequency distributions (defined over a large area) could be compared to theoretical distributions and the degree of variation between them could be viewed as an index of cumulative effects (Benda et al., 1998). Such an distribution-based index incorporates the temporal and spatial scales relevant to environmental impacts that occur over time at the scale of watersheds or landscapes.

Although long time trends were used to develop the theoretical distributions presented in this paper, it may be possible to construct empirical distributions that informs on the natural range of variability. Space for time substitution techniques would be required (Brundsen and Thornes, 1979), as well as whole basin sampling. Information on basin history would be needed to correlate to field data on wood abundance, including the occurrence of large fires, windstorms, floods, landsliding, etc. Studies would need to occur in

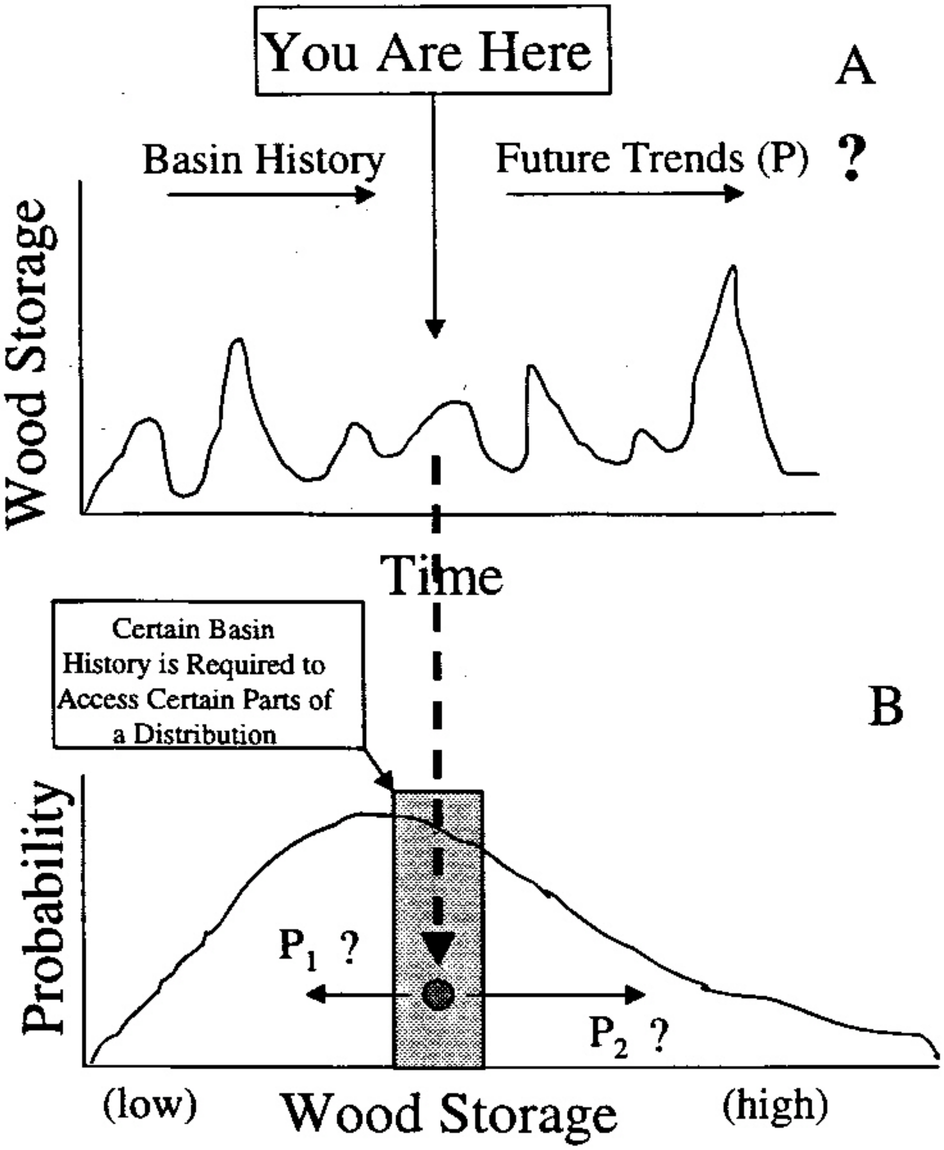


Figure 18. (A) Field measurements of wood in streams are typically limited to a point in time. It is often difficult to know what led to observed wood storage or how wood abundance will change in the future. (B) To understand where an environment in any year resides within its range of variability, a theoretical distribution of storage can be used as a guide to help reconstruct the past (fires, wind, landslides, floods, etc.). That is, the shape of the theoretical distribution informs on what landscape factors and what process rates would be requited to access different portions of the distribution, and hence certain wood storage values. This reasoning, in combination with information on expected future trends in watershed condition (e.g., aging forests, increased landslide hazards, enhanced wind disturbance, etc.), can contribute to more accurate predictions of future patterns of wood loading. That is, knowledge of a basin's likely present position in a theoretical distribution can aid in projecting the future in the form of testable hypotheses (e.g., P_1 and P_2) based on knowledge of evolving conditions in a basin.

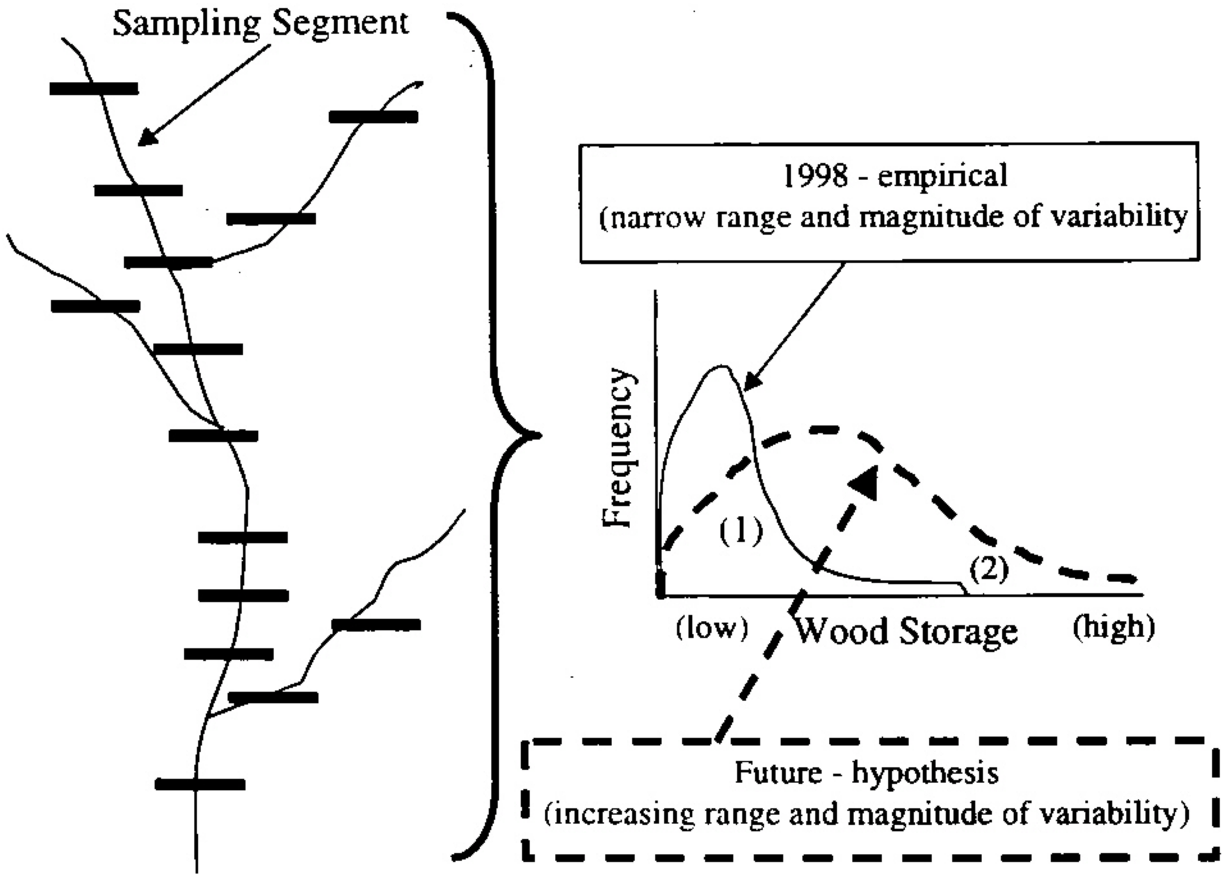


Figure 19. Field measurements at a single point in time within a network (multiple segments) can be used to define an empirical distribution of wood storage. Use of theoretical distributions (applied over the appropriate portion of a network) can generate hypotheses on future expectations (Figure 18). Subsequent field measurements (when an appropriate amount of time has lapsed) can be used to develop another empirical distribution to verify initial hypotheses or predictions. Evaluation of the initial 1998 distribution in this example is expected to shift towards the right center as forests age (1) and towards the right tail (2) because of increased mass wasting.

a range of similar unmanaged watersheds that reflect a range of disturbance histories. If only limited field data were available, as is often the case, theoretical distributions could be used to parlay limited information collected over small temporal and spatial scales into hypotheses on longer-term patterns of wood recruitment, transport, and storage at the scale of landscapes. In this context, an empirical approach could be combined with the theoretical reasoning here to help define the natural variability of wood abundance.

4.3 Establishing Realistic Targets for Wood Recruitment and Storage

Another practical application of wood budgeting linked with theory (summarized in Figures 16 and 17) is defining more realistic targets for future wood loading in channels in the context of forest management planning, habitat conservation plans (HCPs), and associated monitoring programs. Frequency distributions of wood recruitment and storage may be more realistic than single values (averages), since distributions account for all the processes which would tend to give values other than the mean, such as recent fires (or harvest), landslides, floods, etc. For example, mean values appear to be more appropriate in landscapes with low disturbance while the range of variability, or some measure of the variance, may be more appropriate in landscapes with high fire frequencies or rates of mass wasting. Furthermore, theoretical distributions of wood storage could also foreseeably be used to develop similar distributions of channel morphology, including pool spacing etc.

5.0 Conclusions

Five landscape processes were evaluated for their effects on the range and magnitude of woody debris in streams: (1) Frequency of stand-resetting disturbances and the subsequent trajectories of forest biomass accumulation and stand mortality; (2) intensity of bank erosion and its spatial variance in a network; (3) temporal and spatial frequency of mass wasting; (4) fluvial transport controlled by number of upstream contributing segments and wood loss through export or off-channel storage; and (5) rates of wood decay. Periodic vegetative disturbances, such as fires, in environments with low bank erosion, lead to two distinct states of wood loading: (i) A chronic rate of wood flux from gradual stand mortality, and (ii) infrequent pulses of wood associated with toppling of fire-killed trees. In such environments, distributions of wood loading and storage are positively skewed (moderate to low values are common, high values do occur but are uncommon). Longer fire cycles (> 200 yrs), such as characterizes west-side forests in the region, yield longer periods of greater recruitment rates and larger maximum rates since standing biomass generally increases with forest age. Shorter fire cycles (< 200 yrs), more indicative of east side and southern forests in the region, have longer periods of low wood loading and lower maximum recruitment rates. In general, increasing disturbance compresses the range and magnitude of variability while decreasing disturbance has the opposite effect. Because bank erosion can recruit to a channel essentially all trees that are undercut, even low bank erosion rates contribute significantly to the overall wood supply. Bank erosion greater than approximately 6 cm yr^{-1} can dominate wood loading when stand mortality is the only other recruitment process. Very large bank erosion rates (~0.5 m+ per year) can overwhelm all other wood sources and de-emphasize pulses of wood from fires or landsliding.

Other hypotheses include that mass wasting (such as debris flows in the Pacific Northwest) represents the single largest point source of wood to a channel (or valley floor), fluxing even larger volumes than post-fire toppling of trees. However, because of the low frequency of debris flows (about one every 3 to 6 centuries in first- and second-order channels) compared to the relatively short lifespans of wood because of decay (on the order of several decades for individual logs), the overall contribution to the long-term wood mass balance is low, about 10% - 15%. As a consequence, the effect of low frequency mass wasting is to alter the far-right tail of the frequency distribution of storage. However, over shorter periods (decades), or in areas of higher levels of disturbance, wood loading by mass wasting can overwhelm all other wood recruitment sources.

We evaluated the effect of stream transport of wood which included rapidly increasing the variability of wood storage with increasing distance downstream in a network. Transport of wood can modify the shapes of frequency distributions of storage (or flux) in a progressive fashion downstream. Wood transport shifts the distribution of wood storage (the distribution in the absence of transport), both towards the left (i.e., lower wood storage) when jams fail and towards the right when jams form and wood is captured. The relationship between wood storage and drainage area (e.g., either increasing or decreasing storage downstream) depends on the number of upstream contributing segments and whether wood is lost through export or through off-channel storage.

The similarly between the predicted range of piece frequencies and field measurements (in unmanaged west-side forests) indicate that our simplified (coarse grained) analyses of wood storage and piece frequencies are sufficient to reproduce values of wood loading that occur in nature. This is a consequence of the relatively narrow ranges of landscape process rates that occur within a single physiographic region (such as fire cycles, bank erosion, debris flows, decay rates etc.) which constrain the relative range and magnitude of variation in wood flux and storage. In addition, relatively narrow regional ranges of stand density, piece breakage, tree heights, and geometry of random tree fall ultimately restrict how many pieces will be introduced to a channel from a streamside forest (in a non transport case), constraining the absolute magnitude of piece frequencies. Therefore, because process rates and riparian forest characteristics vary across different physiographic areas (say west to east across the Cascade Mountains), one should be able to relate interregional differences in wood storage (in terms of piece frequency) to differences in climate, land-cover history (including the effects of fire and land management), and topography. The analysis also allows predictions of the average wood production (or flux) rate in terms of number of pieces or volume/km^2/yr which may be useful for considering wood loading to estuaries or oceans (Gonor et al., 1988).

The theoretical analysis of wood abundance in streams has practical applications in the context of forest management, environmental assessments, monitoring programs, and restoration. These include: (1) Providing a framework for constructing wood budgets, including estimating the range and magnitude of variability of wood abundance; (2) generating testable hypotheses on current and future wood loading; and (iii) setting realistic targets for wood recruitment and storage. The general principles outlined in this study are dependent on the state of knowledge of landscape processes, structure of streamside forests, and wood storage in streams. In this study, information about many of these attributes were gleaned from previous research. It is expected that hypotheses generated by the theoretical framework will, at times, be rejected when contrasted with field data and hence field observations may not accord with the inferences made in this study. Such failures are necessary in any scientific venue and should be viewed positively in that modifications can be made to improve the general theory. In addition, with continued improvements in regional databases of landscape process rates the approach that we have outlined could be expanded to include wind disturbances and other types of mass wasting. In later papers, complicated mixtures of wood recruitment and transport processes will be analyzed to further define the stochastic behavior of wood loading in streams and rivers in the region.

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