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Little North Fork Noyo River Wood Budget

Mendocino County, California

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Executive Summary

A wood budget was constructed for the Little North Fork (LNF) Noyo River basin near Mendocino, California. Over 7 km of channels were surveyed to determine the rates of wood recruitment by forest mortality, bank erosion, and streamside landsliding, and to estimate wood loading from historical logging activities. The wood budget was also used to estimate rates of bank erosion and forest mortality.

Seven reaches were surveyed that ranged from 400 to 2,500 m in length and totaled 7.6 km. Study reaches ranged from 1 to 7 meters in width with slopes from 1 to 9%. Wood was the dominant pool former in most study reaches. Wood storage and recruitment rates exhibited high spatial variability (hundreds to thousands of percent) at the 100 m reach scale due to variation in recruitment processes and in amounts of historical logging debris. On average, logging debris comprised 22% of the total in-stream wood. Bank erosion comprised 81% of wood recruitment followed by mortality (11%), landslides (6%), and debris flows (2%). Because bank erosion was the dominant recruitment process, approximately 90% of the wood enters the channel from within 8 m (slope distance) of the stream edge.

Total wood storage ranged from 2 to 95 $m^3/100$ m and averaged 18 $m^3/100m$. Wood recruitment rates averaged 2.1 m^3 km^{-1} yr^{-1} for all processes combined, with 0.3 m^3 km^{-1} yr^{-1} for mortality, 1.6 m^3 km^{-1} yr^{-1} for bank erosion, and 0.2 m^3 km^{-1} yr^{-1} for landsliding. Ages of log jams and distances between jams reflect instream wood transport. Debris jam age (average 30 years) decreased with increasing drainage area indicating increasing wood transport and decreasing jam stability downstream. The distance between debris jams averaged 73 m and interjam spacing showed an increasing trend downstream. Assuming that in-stream wood survives approximately 100 years before decaying (using an average 3% yr^{-1} decay rate), predicted transport distances over the lifetime of wood averaged 440 m.

Wood recruitment data were used to predict rates of forest mortality and bank erosion. Based on stand surveys of trees greater than 10 cm in diameter near in-stream wood survey sites, conifers comprised over 90% of the riparian forest with average riparian forest biomass of 515 m^3 ha^{-1} (conifer 485 m^3 ha^{-1}, deciduous 30 m^3 ha^{-1}). Forest mortality rates for conifer and deciduous trees averaged 0.3% yr^{-1} and 0.1% yr^{-1}, respectively. This contrasts with the estimates of second growth forest mortality in the Van Duzen watershed of 0.9% yr^{-1} and 0.6% yr^{-1} for conifer and deciduous trees, respectively, where deciduous trees comprise half of the riparian biomass. The data suggests that trees are dying slower in the Mendocino County study basin. This may be partly due to the dominance of redwood trees which have an overall lower forest death rate particularly as they age (Benda et al. 2002a).

Average bank erosion rates for larger, fish bearing streams was estimated to be 7 cm yr^{-1}, a rate that may reflect continuing incision and lateral migration of the channel because of past logging that either filled channels with sediment or otherwise altered their hydraulic geometry. A bank erosion sediment flux for 3rd and higher order channels of 410 t km^{-2} yr^{-1} was calculated for the LNF Noyo. In the context of other independent estimates of sediment yield along the Mendocino Coast, the calculated sediment flux from bank erosion is a major component of the LNF Noyo's sediment budget. More specifically, the rate of 410 t km^{-2} yr^{-1} for fluvial bank erosion is *inconsistent* with the estimated bank erosion sediment input rate of 77 tons km^{-2} yr^{-1} contained within the Noyo River total maximum daily load (TMDL) for sediment (U.S. EPA 1999) based on the "desk top" sediment budget of Graham Matthews & Associates (GMA) (1999). This suggests that the EPA TMDL for the Noyo River has underestimated the bank erosion component of the sediment budget by approximately 500% and consequently the "background" sediment yield by 250%, despite the claim by the EPA in the Noyo River TMDL (1999) that "the 77 tons km^{-2} yr^{-1} [for bank erosion] is likely an overestimate..." Consequently, lingering effects of past logging activities may dominate present day erosion and sediment yield, a situation that cannot be significantly altered by present day forestry activities. The apparent underestimation of the bank erosion component and hence the background sediment loading of the Noyo River watershed contained within the EPA TMDL for the Noyo River suggests that the use of quantitative values (from the TMDL) should be treated with significant caution and potentially not be used for establishing quantitative thresholds for monitoring, etc.

In LNF Noyo River basin, results from the wood budget have the following implications for forest management:

1. Total wood storage and recruitment rates of wood are highly variable and indicate that very long (over 7 km) continuous surveys are needed to establish a reliable (spatially stable) average value of wood storage in any individual basin. Part of the spatial variability is driven by the temporal dynamics in wood recruitment that is anticipated to be high given that recruitment is dominated by non-mortality sources (bank erosion and stream side landsliding). Hence, the stochastic behavior of storms and floods should drive significant variability in wood storage over time. This behavior is compounded by basin-scale differences in wood recruitment linked to variation in topography and forest biomass, among other things. All of these complexities suggest that establishing regional targets for wood loading and conducting compliance monitoring is questionable in the naturally dynamic and spatially heterogeneous environments in northern California. In addition, it also suggests that establishing wood loading targets, if necessary, needs to be specific at scales ranging from individual watersheds to individual reaches.
2. The dominance of non-mortality sources of wood recruitment indicates that design of buffer strips for wood recruitment may need to consider landforms prone to bank erosion and stream side landsliding. Source distances for wood recruitment greatly depend on whether bank erosion or streamside landsliding are important processes; forest mortality is typically a tertiary process in wood recruitment. Hence, design of buffer strips might be most effective at a site specific basis, in which the width of the buffer strip will vary along a stream according to variations in wood recruitment processes.
3. Information on wood transport indicates that only the lower portions (< 200 m) of small, headwater non-fish bearing streams contribute wood to larger, fish-bearing channels.
4. It may prove informative to construct simulation models for examining and illustrating long-term trends in channel wood storage (e.g., U.S. Forest Service 2002) for the LNF Noyo watershed to contrast the effects of past and future forest management and stream cleaning activities. This will require parameterizing rates of forest mortality, bank erosion, and landsliding, and these values can be obtained from the wood budget analysis contained herein.

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1. Introduction/Study Objectives

The management, regulation, and restoration of in-stream wood are becoming commonplace because of the recognized importance of wood in aquatic and riparian ecosystems. This may include establishing performance standards and monitoring programs to verify compliance. Most existing concepts and quantitative models consider recruitment from mortality only (Welty et al. 2002) and none of the current regulatory approaches considers recruitment from other processes (i.e., bank erosion, landsliding, etc.). In addition, none of the regulatory policies consider spatial and temporal variability in wood recruitment or other complexities of dynamic landscapes when defining wood recruitment and monitoring targets.

Wood in streams can be evaluated in terms of its mass balance, similar to budgets in other environmental systems such as water, sediment, or carbon (Benda and Sias 2003). Constructing a wood budget can be used to estimate the relative importance of different climatic, vegetative, and geomorphic processes on wood abundance in streams, including mortality, bank erosion, fires, windstorms, and landsliding across a range of spatial and temporal scales. In addition, wood budgets can also be used to predict the importance to in-stream wood supply of large regional disturbances, such as wildfires, floods, hurricane-force windstorms, and widespread mass wasting. This information could be helpful in quantifying the range of variability in wood supply and storage, and to make predictions about how differences in landscape attributes (climate, topography, etc.) and land management lead to differences in wood abundance.

Wood budgets applied at the scale of whole watersheds can provide a useful tool for establishing realistic goals for wood management that consider spatial and temporal variability in recruitment processes. Foresters and fisheries biologists can apply that information to develop forest management prescriptions to ensure adequate wood supply to streams. Wood budgeting can also be used to estimate rates of forest mortality, bank erosion, and landsliding, information useful to foresters, ecologists, and geomorphologists. Such information can be used to develop sediment budgets or to verify and refine existing estimates of sediment production.

This report contains an analysis of the wood budget for the Little North Fork (LNF) Noyo River watershed, a tributary basin in the Noyo River located approximately 10 km east of Fort Bragg, California (Figure 1). Forest mortality rates are also estimated using results from the wood

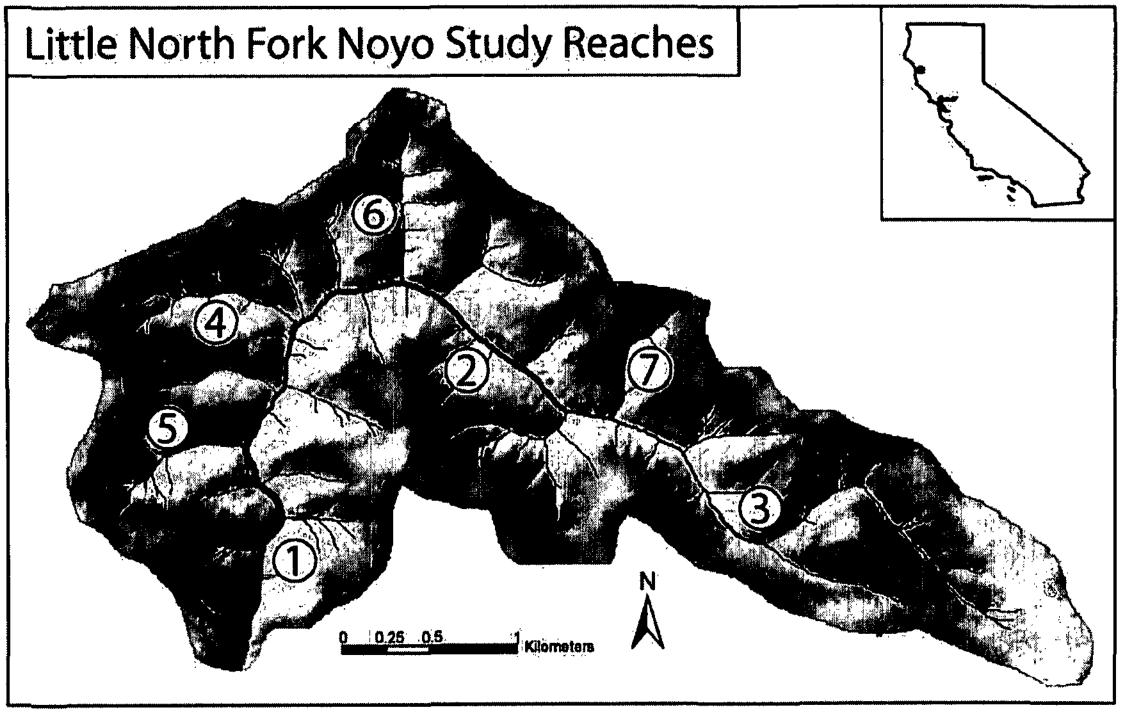


Figure 1 - The LNF Noyo River basin with study reaches identified by number. Refer to Table 1 for details on individual study reaches.

budgets and they can be used to parameterize wood recruitment models. Results from the wood and sediment budgets from the LNF Noyo basin can be extrapolated to other areas with similar geology, topography, and channel types. Hence, results from wood and sediment budgets can form a foundation for addressing issues pertaining to woody debris in channels and basin erosion rates.

2. Study Areas

Field sites were selected to identify the range of processes and rates of wood recruitment in second-growth redwood forests in a sub-basin of the Noyo River drainage of Mendocino County, California (Figure 1). Approximately 7.6 km of channels were surveyed within the LNF Noyo River watershed that has a drainage area of approximately 10 km^2.

Surveys were conducted along seven reaches (7.6 km total distance) in 1 to 7 m wide channels with morphologies that ranged from steep and boulder bedded (7%) to lower-gradient plane-bedded and gravelly (1%) (Table 1, Figure 1). The dominant channel morphology was

Table 1 - Study site physical characteristics.

Reach No.	Drainage Area (km^2)	Stream Class	Reach Length (m)	Average Slope (%)	Ave Channel Width (m)	Dominant Substrate	Sub-Dominant Substrate	Channel Type	Pool Former (%)		
									Wood	Boulder	Bedrock
1	9.5	I	1500	1	7.0	Gravel	Cobble	PR / FP	78	17	6
2	6.9	I	2500	1	4.7	Gravel	Cobble	PR / FP	77	0	23
3	1.9	I	800	2	2.5	Sand	Gravel	PB / FP	70	0	30
4	0.6	II	900	7	1.8	Sand	Gravel	SP / FP / PB	100	0	0
5	0.3	II	800	8	1.2	Sand	Gravel	SP / FP / PB	100	0	0
6	0.5	II	700	5	1.8	Sand	Gravel	SP / FP / PB	50	0	50
7	0.4	II	400	9	1.0	Sand	Gravel / Cob	SP / FP / PB	100	0	0
		Total:	7600					**Average:**	82	2	15

Notes:

FP - forced pool
PR - pool-riffle
SP - step pool
PB - plane bed

pool-riffle/forced pool in lower gradient streams and step-pool/forced pool (caused by wood) in steeper reaches (Table 1). Gravel and cobbles were the dominant and subdominant substrate in lower gradient reaches, while sand and gravel were the dominant and subdominant substrates in higher-gradient reaches (Table 1). Wood was the dominant pool former (82%), followed by bedrock (16%) and boulders (2%) (Table 1).

The Mediterranean climate of northern California is characterized by high annual precipitation (150-200 cm) that falls primarily between October and April and summer drought with persistent coastal fog (Harden 1995). Redwood (*Sequoia sempervirens*) is the dominant tree species in coastal areas (including LNF Noyo basin) while Douglas fir (*Pseudotsuga menziesii*) becomes more dominant inland. Grand fir (*Abies grandis*) and Western hemlock (*Tsuga heterophyla*) are minor conifer species in the study area. Tan oak (*Lithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), and Live oak (*Ouercus wislizenii*) are mixed with conifers in inland areas, while Red alder (*Alnus rubra*), Willow (*Salix lasiandra*), and Big leaf maple (*Acer macrophyllum*) are the dominant deciduous tree species in riparian areas

Logging of the Noyo River watershed began in the 1850s and over half the timber in the watershed was harvested by 1930 (U.S. EPA 1999). Tractor harvest of second growth and residual old growth began in the 1940s (Graham Mathews & Associates [GMA] 1999). Legacy logging impacts were apparent in all study sites, including mechanical (i.e., tractor) removal of in-stream wood (stream cleaning) in high-order fish bearing streams, while slash and sediment filled channels that are currently incising and unstable were evident in lower order streams.

The geology of the northern California coastal region is characterized by mélanges of the Franciscan complex, a mixture of highly deformed and weakly metamorphosed sedimentary rocks that are mixed with some marine volcaniclastic sediments (Cashman et al. 1995). Mechanically weak rock in combination with heavy rainfall and earthquake activity has created a steep landscape highly prone to mass wasting and produces some of the highest erosion rates in the continental United States (Nolan and Janda 1995). The LNF Noyo basin is underlain by fairly coherent bedrock (sandstone with interbedded siltstone and shale) of the Franciscan Coastal Belt Terrane, which is overlain by a variety of surficial deposits, including landslide debris, alluvial terraces, colluvium, and soil (GMA 1999).

3.1 Quantitative Framework

Similar to other environmental systems (i.e., water, sediment, or carbon budgets) in-stream large woody debris can be evaluated in the context of a mass budget (Benda and Sias 2003). The volumetric mass balance of wood is governed by differences among input, output, and decay, a relationship that can be expressed as:

$$\Delta S = [I\ \Delta x - L\ \Delta x + (Q_i - Q_o) - D]\Delta t \qquad (1)$$

where ΔS is a change in storage within a reach of length Δx over time interval Δt. Change in wood storage is a consequence of wood recruitment (I); loss of wood due to overbank deposition in flood events and abandonment of jams (L); fluvial transport of wood into (Q_i) and out of (Q_o) the segment; and in situ decay (D). I and L have units of volume per unit reach-length per time, and the remaining terms (Q_i, Q_o, and D) have units of volume per time. All of the terms are also functions of location (position in a network). The principle components of a wood budget are summarized in Figure 2.

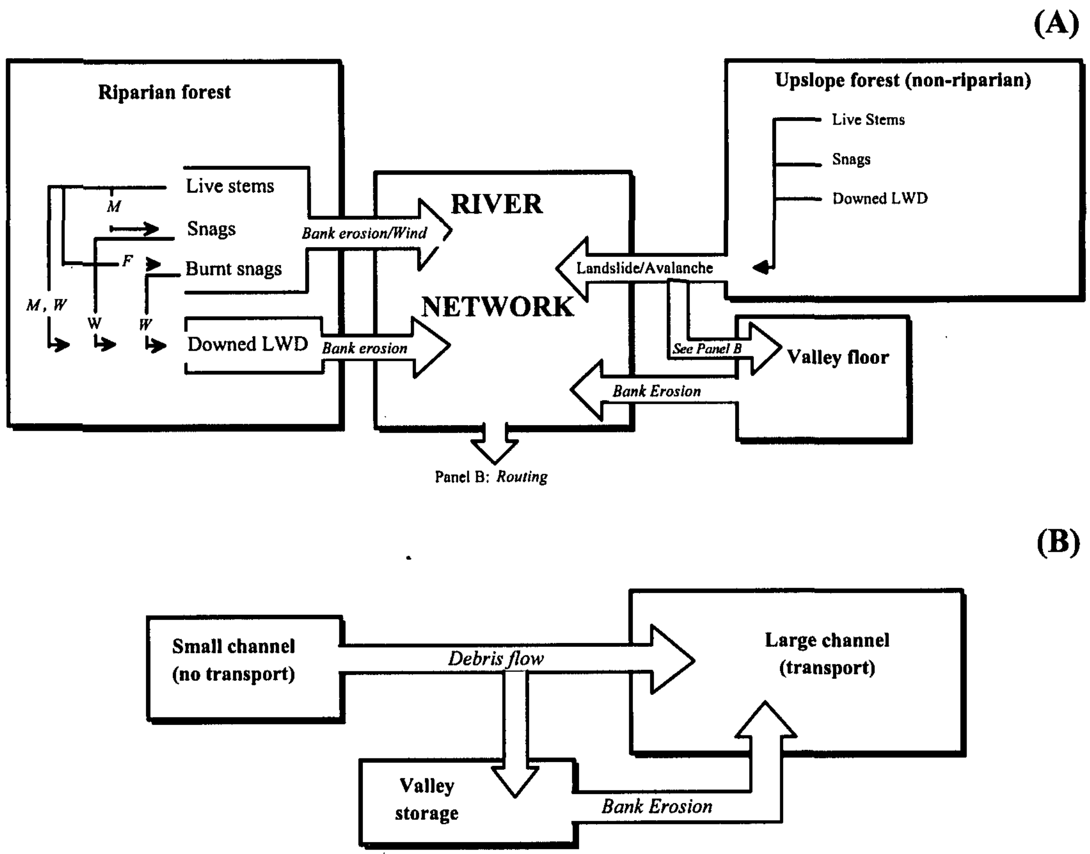


Figure 2 - Flow chart showing the principle components of a wood budget (from Benda and Sias 2002).

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

$$I = I_m + I_f + I_{be} + I_l + I_e \quad (2)$$

Inputs include tree mortality by suppression, disease, or sporadic blowdown (I_m); toppling of trees following stand-replacing fires and windstorms (I_f); punctuated inputs from bank erosion (I_b); wood delivered by landslides, debris flows, and snow avalanches (I_l); and exhumation of wood buried in the bed or bank or the recapture of wood previously deposited on the banks (I_e).

In the solution of Equation 1, the loss of volume due to decay was omitted because our estimates of recruitment over an approximately four decades would be insignificant since decay occurs primarily as a loss of mass due to decreasing wood density (Hartley 1958). In addition, although we observed exhumation of buried wood from debris flow deposits, we set I_e to zero because we could not date the partially buried wood (necessary for estimating recruitment rates). To circumvent this limitation, however, we employ theoretical predictions to constrain the relative importance of debris flow recruitment of wood (in the discussion). Furthermore, in the small to moderate sized channels in the study area, we did not observe wood being deposited onto off-channel areas, such as terraces, and hence we set L in Equation 1 to zero. Given these constraints in our short-term wood budget, Equation 1 reduces to:

$$\Delta S / \Delta t = [I + (Q_i - Q_o)] \, \Delta x \quad (3)$$

The primary objective for constructing wood budgets in LNF Noyo basin was to estimate the relative importance of different recruitment processes, namely mortality, bank erosion, and landsliding. Hence, we did not need to quantify flux due to wood transport and we set $Q_i = Q_o$ in Equation 1. However, we did assess certain aspects of fluvial transport of wood, including mean transport distance. With the fluvial flux terms omitted, equation 3 becomes:

$$(I_m + I_{be} + I_l) = \Delta S / \Delta x / \Delta T \quad (4)$$

where the input rates (ΔI) are the change in recruited wood storage (ΔS) over the length of the study segments (Δx) over some elapsed time period (ΔT). Piece volume was computed from piece length and average diameter using the geometry for a cylinder. T was assumed to be equal to the weighted mean age of recruited wood in that segment (Murphy and Koski 1989; Martin and Benda 2001) computed by:

$$\Delta T = \{\sum_{i=1}^{n} a_i p_i\} \quad (5)$$

where a_i is the mean age of wood in decay class i and p_i is the proportion of wood in decay class i in any segment. ΔT, over short time periods, is sensitive to the sequence of recruited trees of various sizes (i.e., ΔT would be significantly different if a large tree fell in year 10 versus year 1 during a 10-year period). Hence, the proportion of wood in each decay class was based on number of trees, rather than on volume, to reduce the variability in ΔT that can arise due to variations in the temporal sequence of volumetric recruitment. Preferentially weighting the oldest wood in Equation 5 will yield an overestimate in the mean age of recruited wood. However, this error is countervailed by the loss of wood with increasing age, a process that would tend to underestimate the mean age in Equation 5. These potential errors are discussed at the end of the report.

The flux of wood to streams by chronic forest mortality can be expressed as:

$$I_m = [B_L * M_C * H * P_m] * N \qquad (6)$$

where I_m is annual flux of wood [$m^3 \cdot km^{-1} \cdot yr^{-1}$]; B_L is the volume of standing live biomass per unit area [$m^3\ ha^{-1}$]; M_c is the rate of mortality [yr^{-1}] (fraction of live biomass per unit time); H is average forest height [m]; P_m is the stand-average proportion of standing trees that becomes in-channel wood when trees fall within a stream-adjacent forest; and N is 1 or 2, depending on whether one or both sides of the channel are forested (Benda and Sias 2003). Several of the parameters in Equation 6 are functions of time, namely B_L, M_c, and H. However, time dependence is excluded in Equation 6 since recruitment rates, and hence mortality rates in this study, are analyzed over 2 to 4 decades.

P_m is predicted by applying a random geometric tree fall model (Van Sickle and Gregory 1990) to a hypothetical uniform stand of trees within a distance H normal to the bank. P_m is simply the stand-average ratio of the total amount of stem length (from all trees) that intersect a stream channel to the total surface area covered by the random, 360^O fall of all trees. Our calculation of P_m assumes that trees are cylinders because we were unsure of how taper of the bole varies with species, height, and tree age across all study sites. The parameter P_m is dependent on channel width and tree height and predicted P_m values for all study sites are listed in Table 2.

Table 2 - Summary of wood budget parameters.

		Ave Tree Height (m)		P Values			Biomass Density (m3/ha)			Weighted Mean Age (yr)			
Site No.	Stream Width (m)	Decid	Conifer	Erosion	Decid Mortality	Conifer Mortality	Total	Decid	Conifer	Erosion	Decid Mortality	Conifer Mortality	Slide
1	7.0	7.6	27.0	0.47	0.12	0.09	366	0	366	20	15	27	--
2	4.7	19.8	38.8	0.28	0.08	0.05	772	65	707	20	4	13	11
3	2.5	12.0	27.0	0.22	0.07	0.04	909	54	855	24	--	17	--
4	1.8	8.8	24.6	0.18	0.06	0.03	151	0	151	31	--	36	--
5	1.2	12.0	29.0	0.11	0.04	0.02	378	30	348	29	21	28	--
6	1.8	8.2	8.8	0.37	0.06	0.06	515	30	485	36	--	42	--
7	1.0	--	8.4	0.24	--	0.04	515	30	485	34	11	42	--
Averages													
Little NF Noyo	2.9	11.4	23.4	0.27	0.07	0.05	515	30	485	28	12	29	11
Bear Haven	3.0	11	18	0.32	0.18	0.11	333	32	301	19	15	30	34
Redwood	4.2	11	23	0.36	0.22	0.11	539	34	504	19	15	17	13
Van Duzen	7.8	--	--	0.42	0.09	0.09	510	--	--	10	9	9	7
RW Old Growth	16.0	--	--	0.39	0.09	0.09	3941	--	--	10	6	9	4

For instance, P_m is approximately 0.11 for a 7.5 m-wide channel and an average 20 m tree height (i.e., 11% of the cumulative length of all trees in a riparian forest intersect the channel)

The flux of wood to streams by bank erosion can be expressed as:

$$I_{be} = [B_L * E * P_{be}] * N \qquad (7)$$

where I_{be} is the annual wood recruitment and E is the mean bank erosion rate ($m \cdot yr^{-1}$) (Benda and Sias 2003). P_{be} *is analogous to* P_m *although its value is different because trees tend to fall* toward the channel when undercut. The calculation of P_{be} assumes a 100% fall probability towards the channel (based on our field observations and on Murphy and Koski 1989, Martin and Benda 2001). Over long periods, bank erosion should occur only along one side of a channel (i.e., N = 1) to maintain stream geometry in long-term steady state (Benda and Sias 2003). Over yearly- to decadal-time periods, however, bank erosion could occur along both sides of a channel, such as during large floods.

Stream transport of wood can affect the wood budget by redistributing wood through a network and by exporting it from a watershed. Field studies indicate that wood transport depends on several factors. Pieces that are transported tend to be shorter than bankfull width (Lienkaemper and Swanson 1987; Nakamura and Swanson 1993; Martin and Benda 2001). Transport distances are also limited by obstructions such as debris jams (Likens and Bilby 1982).

Because channel width increases downstream, an increasing proportion of all wood should become mobile if the distribution of recruited piece sizes remains constant (Bilby and Ward 1989; Martin and Benda 2001). Transport of wood is also affected by stream power (slope and stream cross sectional area). Other complexities (not addressed here) include diameter of logs, piece orientation, and the presence of root wads (Abbe and Montgomery 1996; Braudrick and Grant 2000).

Our objective in estimating wood transport in the LNF Noyo basin is to minimize complexity in order to examine how a few landscape factors (channel or basin size, tree size, jam spacing and longevity) impose constraints on wood transport. Fluvial transport can be defined as:

$$Q_w(x,t) = [I(x,t) * \phi(x,t) * \xi(x,t)] \qquad (8)$$

where Q_w is the volumetric wood transport or flux rate [$m^3 \cdot yr^{-1}$] for segment x in year t (equivalent to Q_i or Q_o in Equation 1), I is the annual rate of lateral recruitment [$m^3 \cdot m^{-1} \cdot yr^{-1}$], ϕ is the long-term proportion of all recruited wood (I) having piece lengths (L_p) less than the channel width, and ξ is transport distance over the lifetime of a wood [m] (Benda and Sias 2003). Decay will tend to convert longer, non-mobile wood to shorter, mobile pieces. It is assumed that the relative proportions of mobile to non-mobile wood remain constant over time (although they may vary spatially in a network) due to continuous tree recruitment (this assumption may not hold during episodes of very high or low recruitment). The transport distance (ξ) over the lifetime of wood is predicted by:

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

where ξ is the mean transport distance [m] over the lifetime of a piece of wood; L_j is the average distance between transport-impeding jams; T_p is the lifetime in years of wood in fluvial environments; T_j is jam longevity in years; and β is the proportion of channel spanned by a jam (Figure 3).

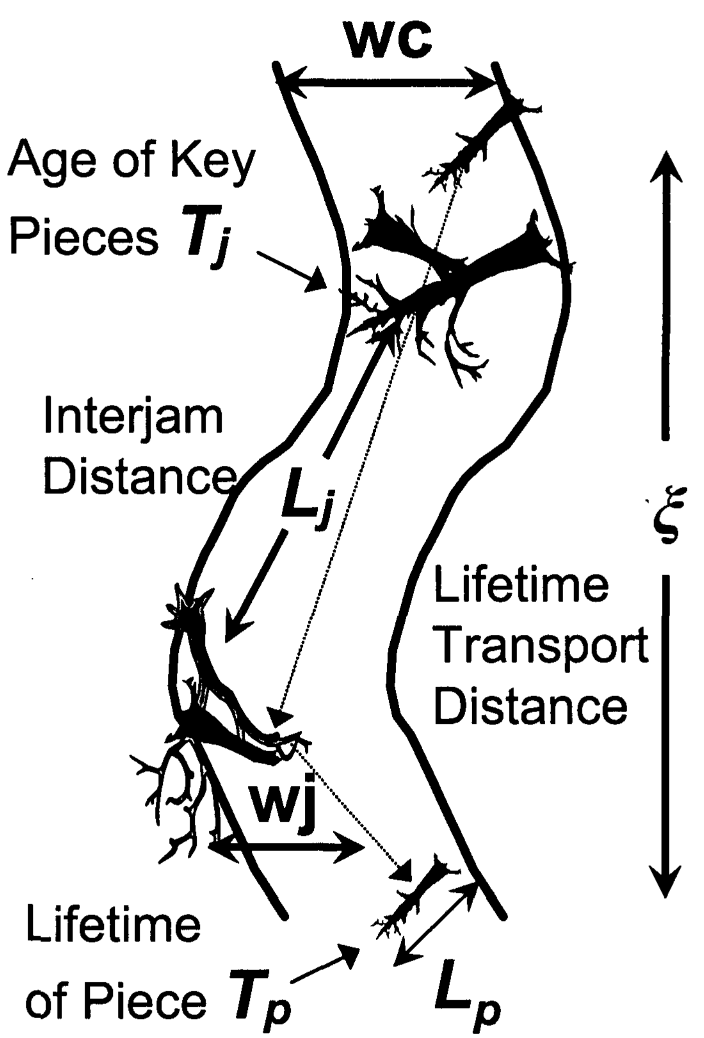


Figure 3 - Sketch showing the principle components of wood transport (Equation 9). Adapted from Martin and Benda (2001).

In this derivation, transport is limited to inter-jam spacing and it can become a multiple of L_j when the lifetime of mobile wood exceeds T_j. A jam may not completely block a channel thereby allowing only a proportion of wood to be captured and stored. In the absence of measurements on how wood transport is affected by the proportion of a channel spanned by a jam, transport of wood is assumed to be inversely and linearly proportional to the ratio of piece length L_p (i.e., pieces creating jams) to channel width (w) (i.e., $\beta = L_p/w$). Effects of flood frequency and magnitude are omitted in Equation 9 based on the assumption that floods of sufficient magnitude will transport wood a distance L_j in the time interval T_j. The lifetime of wood is limited by decay through a process of loss of mass. This eventually weakens logs and allows pieces to break apart into small, highly transportable pieces that are not susceptible to capture by jams. Although loss of mass is an incremental process, it is assumed that breakup of wood into highly transportable pieces occurs instantaneously after a time T_P as a strength threshold is reached.

Equations 8 and 9 apply only to streams and rivers where transport is limited by jams and they do not address transport in larger rivers where other forms of wood storage occur, such as on large floodplain rivers and in off-channel areas. In addition, the wood transport equations do not apply to wood movement at the reach scale over a few years because of the complexities of wood transport that were not included.

3.2 Field Data Collection and Data Analysis

All pieces were inventoried within the bankfull width that were greater than 10 centimeters in diameter (as measured in the middle of the log) and 1.5 meters in length, corresponding, in general, to definitions of "large woody debris" (Sedell and Triska 1977). B_L in Equations 6 and 7 were estimated using stand plot surveys (Campbell Timberland Management 2003, unpublished data). The perpendicular slope distance of each recruited piece of wood from the edge of the bankfull channel to its source (i.e., base of tree) was measured with a tape.

To estimate recruitment rates of in-stream wood, the origin of pieces was identified and this could only be accomplished for a proportion of the total number of pieces. Trees, or pieces of unknown origin (i.e., mobile pieces) had no obvious connection to the adjacent riparian stand and generally showed signs of fluvial transport (abrasion, broken limbs, broken ends, located in log jams). Each tree with an identified source was assigned to one of six source categories: bank erosion, streamside landslide, debris flow, mortality, imbedded, or logging related. Wood recruited by bank erosion had roots connected to the stream bank, or the root wad was in the channel and bank erosion was evident. Wood recruited by landslides was located within landslide deposits. Wood recruited by forest mortality originated from within the riparian forest. Imbedded wood included pieces originating from the channel bed or banks. Some of these pieces may have been deposited by debris flows or pieces that were recruited by other processes were subsequently buried with sediment.

For wood with identified origins (with the exception of imbedded pieces), pieces were assigned a decay class using a modified version of a snag classification system by Hennon and McClellan (2003). The Hennon decay categories that were used included 1) leaves or needles; 2) twigs (no needles); 3) full branches; 4) primary branches; and 5) partial primary branches, 6) no branches and hard wood, and 7) no branches and rotten wood. To assign an age to the decay categories for the pieces of identified origins, annual and perennial vegetation growing near or on the recruited trees or on overturned stumps of recruited trees were dated by counting branch nodes. Larger saplings growing on logs were dated using an increment borer or the bole, or primary stem, was cut with a saw and tree rings were counted.

Using data on distance to wood recruitment sources, we calculated the relative proportion of wood that entered streams from varying distance away from channels banks. The cumulative distributions that were constructed are referred to as "source distance curves" (McDade et al. 1990; Robison and Beschta 1990). For comparison to field data, we also made theoretical predictions of source distance curves for mortality recruitment. To estimate the changing proportion of trees that can intersect a channel from increasing distance away from stream edge, we applied a random 360^{O} fall trajectory for each tree (using a uniform stand density) within a maximum distance of an average tree height normal to the bank (based on the model of Van Sickle and Gregory (1990)). The theoretical source distance curves assume that trees are cylinders; adding taper would reduce the amount of wood originating from distances further away from the channel.

Channel morphology was characterized at the scale of gradient breaks (5 to 20 meters) within each of the study reaches; gradient breaks were determined using a hand-held clinometer. Measurements included: (1) dominant planform morphology (i.e., pool-riffle, plane-bed, step-pool, or cascade); (2) channel gradient (measured with a hand-held clinometer); (3) bankfull width (using visual indictors, including the base of perennial vegetation, changes in bank slope, and evidence of scour or lack of moss [Rosgen 1996]); (4) substrate (visually classified into percentages of bedrock, boulders, cobble, gravel, and sand); and (5) pools with a residual depth over 0.5 m and pool forming element (wood, bedrock or boulder, hydraulic).

4.1 Patterns of Wood Storage and Function

Of all the wood pieces surveyed along the LNF Noyo River (n = 2609), 26 percent were identified to a recruitment process of landsliding, debris flow, bank erosion, forest mortality, or logging debris. Field measurements revealed high spatial variability in total wood storage and wood recruitment along the cumulative 7.6 km of channels surveyed. Total wood storage ranged from 13 to 95 m^3/100 m and averaged 18 m^3/100m (Figure 4A, Table 3). On average, total

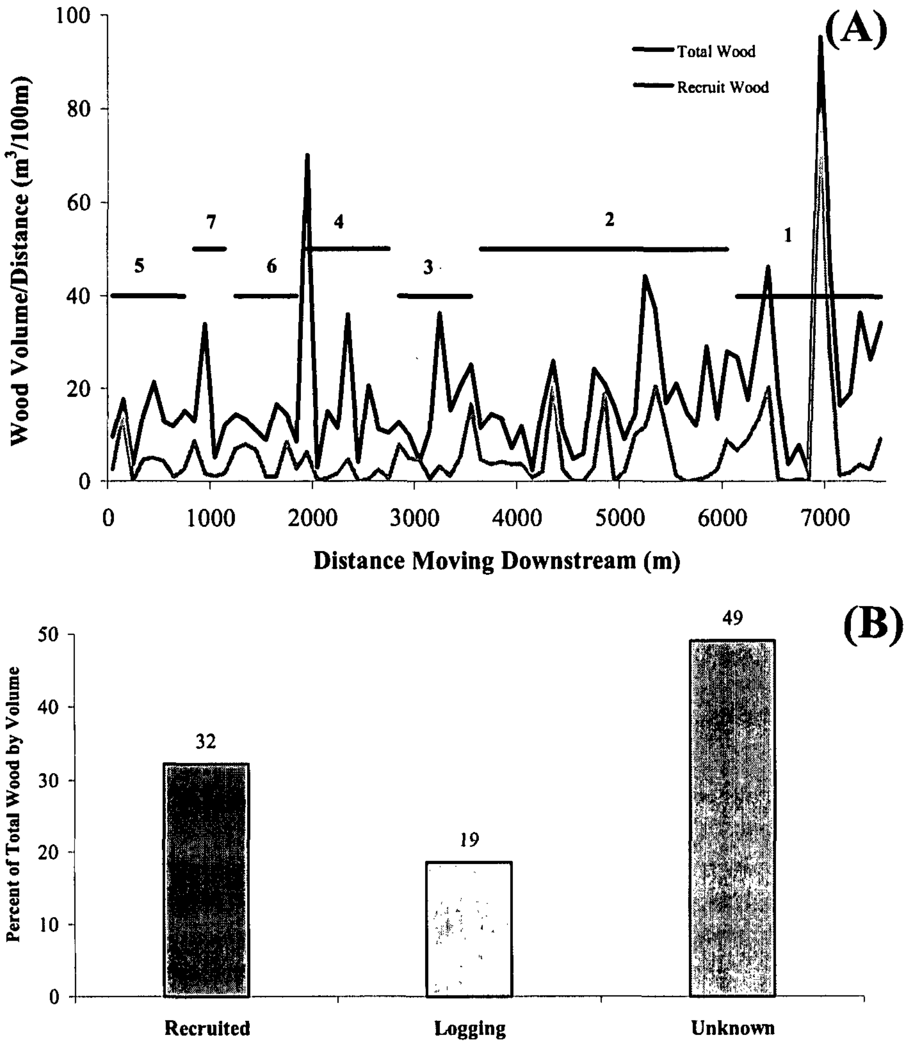


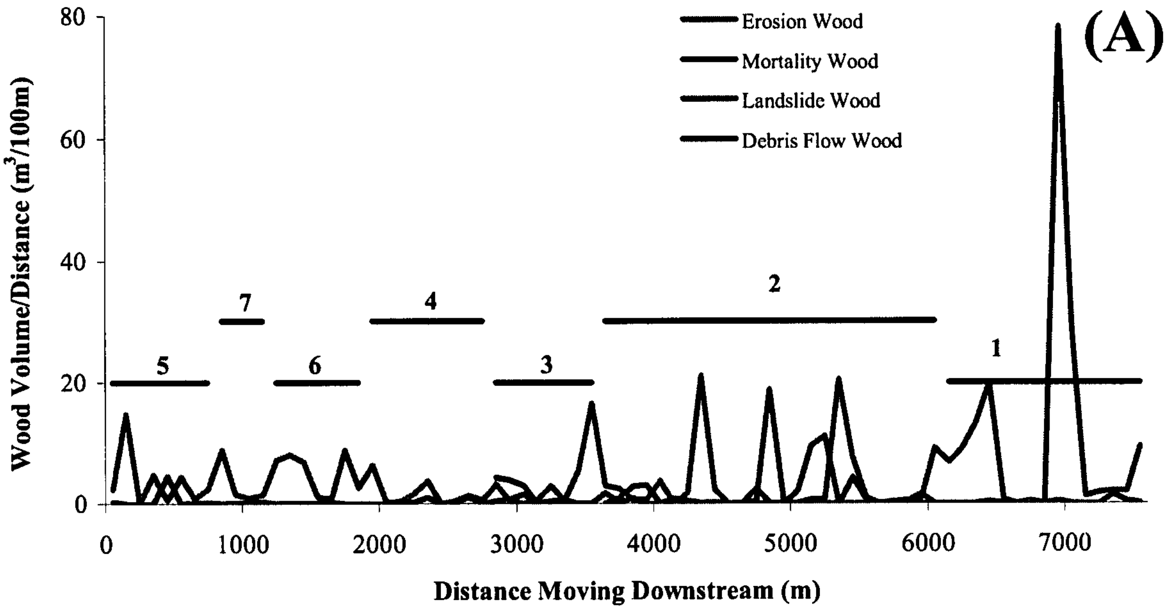
Figure 4 - (A) Spatial variation in total and recruited wood storage volume by distance. Black horizontal lines denote study reaches that are plotted from smallest to largest drainage area (i.e., distance moving downstream). (B) Percentage of total wood volume related to a natural recruitment processes, logging, or unknown sources (e.g., mobile or highly decayed wood).

Table 3 - Summary of wood volumes per distance.

	Total Wood (m^3/100m)			Logging Wood (m^3/100m)			Logging Wood	Wood Recruit Volumes/Distance (m^3/100m): Erosion			Mortality			Slide			Debris Flow			Total Recruits			% Recruits by Volume		Number of Recruits		Ave Recruit Diameter
Site No.	**ave**	**min**	**max**	**ave**	**min**	**max**	**(% of Total)**	**ave**	**min**	**max**	**ave**	**min**	**max**	**ave**	**min**	**max**	**ave**	**min**	**max**	**ave**	**min**	**max**	**con**	**dec**	**con**	**dec**	**(m)**
1	29	2	95	5	0	12	16	12	0	78	0.2	0	1.6	--	--	--	--	--	--	12	0.0	79	97	3	36	25	0.60
2	17	2	44	2	0	9	14	3.2	0	21	1.4	0	11	1.0	0.0	19	--	--	--	6	0.0	21	97	3	81	29	0.48
3	17	5	36	4	0	16	22	3.8	0	17	0.4	0	1.6	--	--	--	1.5	0	4.3	6	0.6	17	95	5	40	6	0.42
4	20	3	70	3	0	19	15	1.6	0	6	0.3	0	1.2	--	--	--	--	--	--	2	0.0	6	99	1	42	2	0.37
5	13	4	21	3	1	6	23	3.8	0.1	15	0.6	0	4.5	--	--	--	--	--	--	4	0.1	15	92	8	30	14	0.49
6	13	9	17	5	3	9	34	5.0	0.8	9	0.1	0	0.2	--	--	--	--	--	--	5	1.1	9	100	0	46	2	0.43
7	16	5	34	5	2	8	29	3.2	0.9	9	0.2	0	0.4	--	--	--	--	--	--	3	1.1	9	99	1	25	5	0.37
Averages																											
Little NF Noyo	18	4	45	4	1	11	22	5	0.3	22	0.5	0	2.9	1.0	0	19	1.5	0	4.3	5.4	0.4	22	97	3	43	12	0.45
Bear Haven	22	11	36	4	1	10	27	1.2	0	4	1.1	0	4.3	0.6	0	3	--	--	--	1.9	0.2	9.5	93	7	16	5	0.36
Redwood	18	7	37	8	1	19	45	0.7	0	4	0.2	0	0.9	0.3	0	3	0.6	0	4.3	2	0.2	8	77	23	23	10	0.31
Van Duzen	97	1	314	19	0	169	20	5	0	27	8	0	42	5.6	0	47	--	--	--	19	0.0	80	50	50	--	--	0.49
RW Old Growth	122	8	411	0	0	0	0	9	0	83	8	0	35	8.4	0	157	--	--	--	26	0.0	169	77	23	--	--	0.85

wood storage volume consisted predominantly of older wood that could not be identified to a source (49%), while the remaining wood was identified with a recruitment process (32%) or related to logging (19%) (Figure 4B).

Variation in wood storage in LNF Noyo River is driven predominantly by spatial differences in wood recruitment from bank erosion, mass wasting, and mortality within the watershed (Figure 5A).



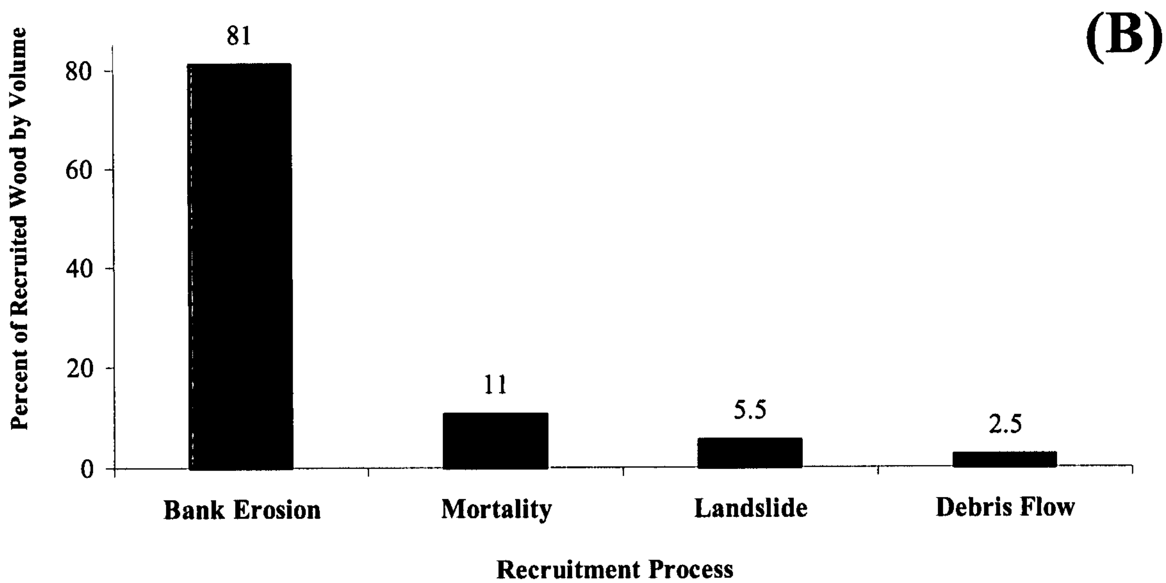


Figure 5 - (A) Spatial variation in recruited wood (bank erosion, mortality, landslides, debris flows) storage volume by distance. Black horizontal lines denote study reaches that are plotted from smallest to largest drainage area (i.e., distance moving downstream). (B) Percent of in-stream recruited wood by process.

Of the recruited wood, bank erosion comprised 81% of recruited wood storage volume followed by mortality (11%), landslides (6%), and debris flows (2%) (Figure 5B). In general, the volume of wood in LNF Noyo River was most similar to wood storage in managed forests of Redwood Creek (Mendocino County), but less than other managed and unmanaged redwood forests in north coastal California (Figure 6).

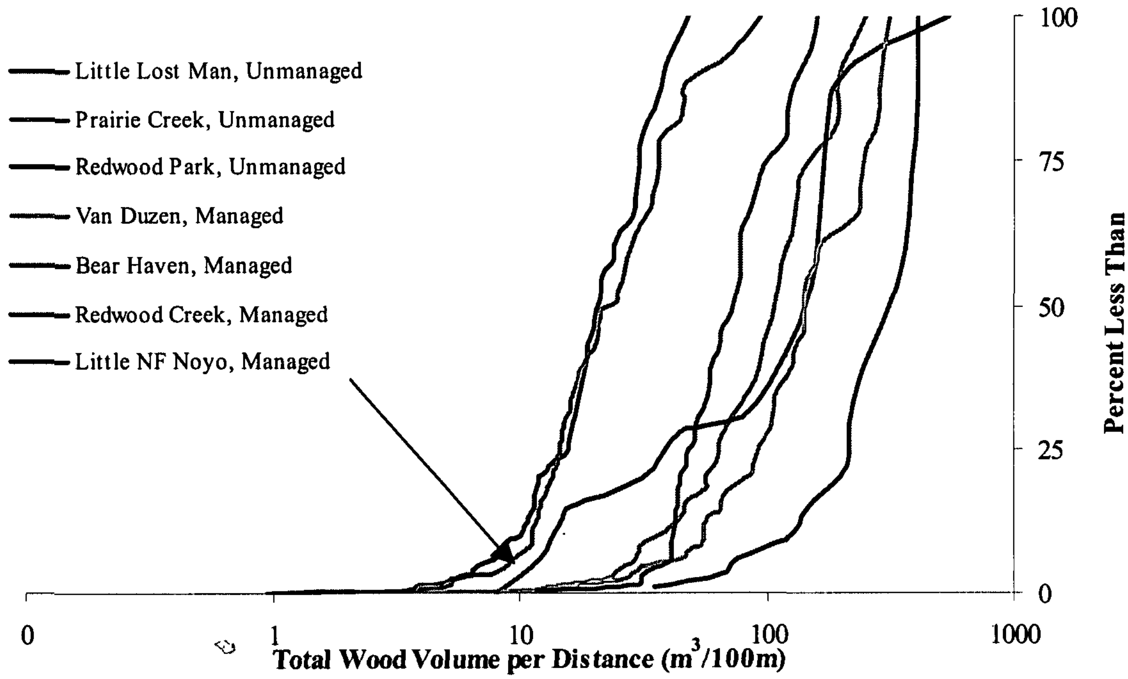


Figure 6 - Cumulative distribution of total wood per 100 meters for streams in old-growth and second-growth forests of California including LNF Noyo basin.

In-stream wood was significant in creating pools in LNF Noyo River, forming 82% of the pools, while bedrock (15%) and boulders (2%) formed the remainder of the pools (Table 1). Further, when plots of wood volume per distance were combined with previous pool surveys (Campbell Timberland Management, unpublished data), pool density appears to increase with wood volume (e.g., Reach #1, Figure 7). In addition to pools, accumulation of wood pieces (wood jams) are

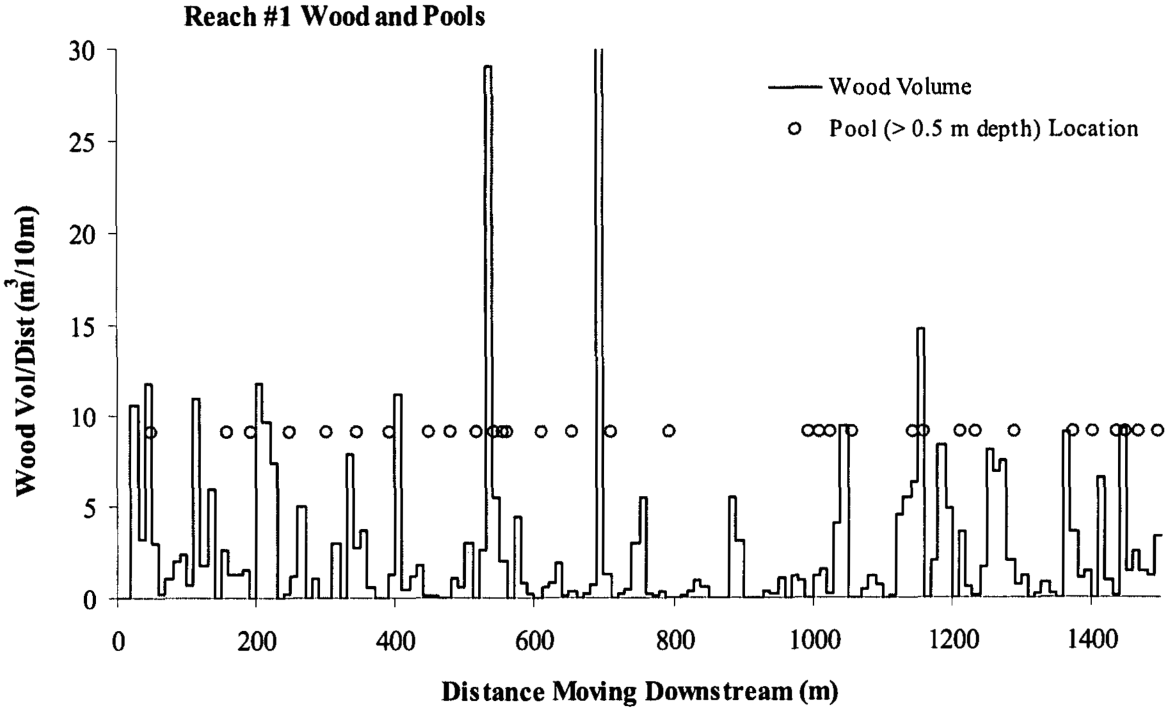


Figure 7 - Total in-stream wood volume per 10 meters and pool locations (Campbell Timberland Management, unpublished data) for Reach #1, visually showing higher density of pools associated with higher wood volumes.

important to aquatic ecosystems (Bisson et al. 1987), for example, jams often store sediment behind them, creating low gradient reaches, and forcing subsurface flow. Key pieces that form and anchor wood jams in LNF Noyo River were most often recruited by bank erosion (68%), followed by mortality (27%) and landsliding (5%) (Figure 8).

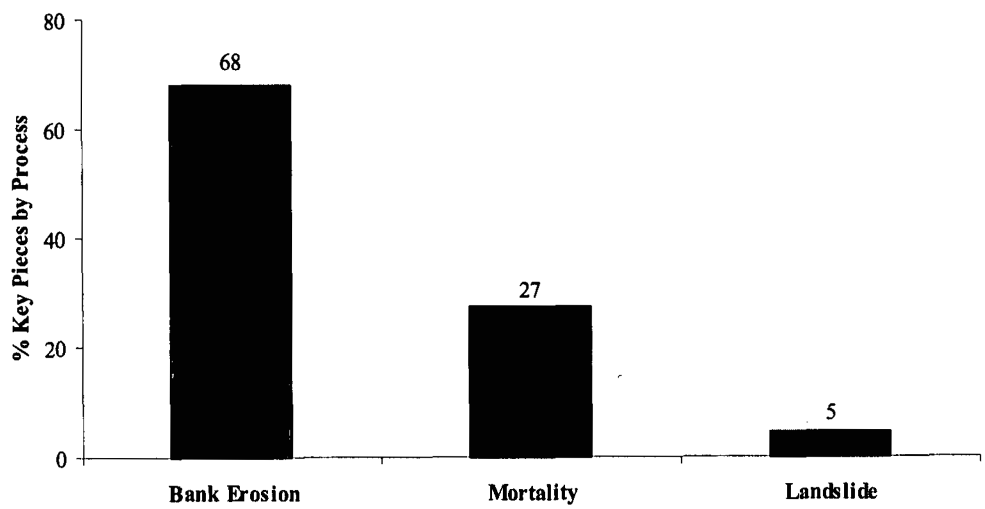
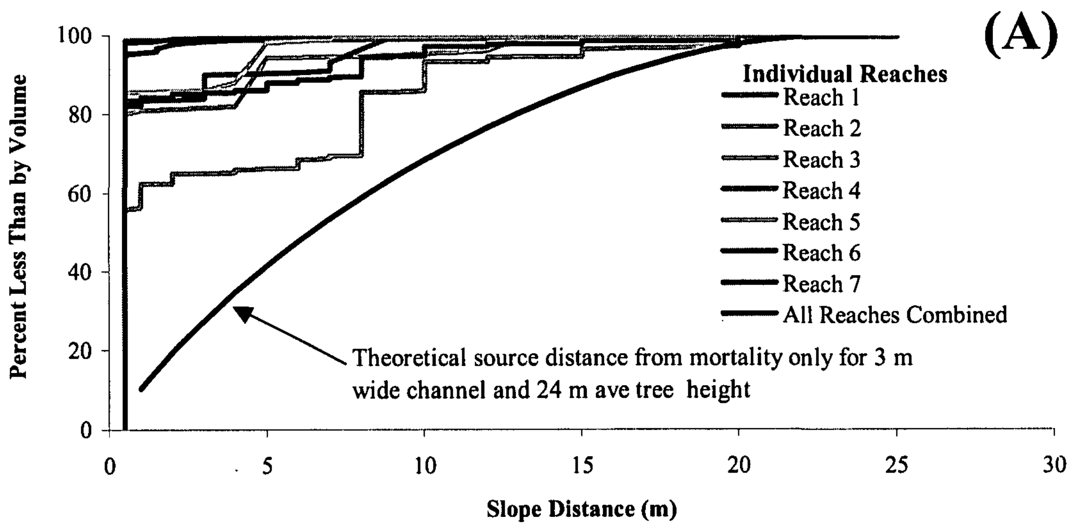


Figure 8 - Percentage of key pieces by recruitment process.

4.2 Distance to Sources of Wood

The distances from wood sources to channels were variable because of the spatial variability in wood recruitment processes in LNF Noyo River (Figure 5). For individual reaches, the source distance appears to be highly influenced by the dominant recruitment mechanisms. For example, in most reaches bank erosion was the dominant recruitment process (Table 3, Figure 5B), and hence source distances were less than the theoretical prediction from mortality alone (Figure 9A). When data are combined for all reaches, 90% of the wood enters the channel from within 8 m (slope distance) of the stream edge (Figure 9B).



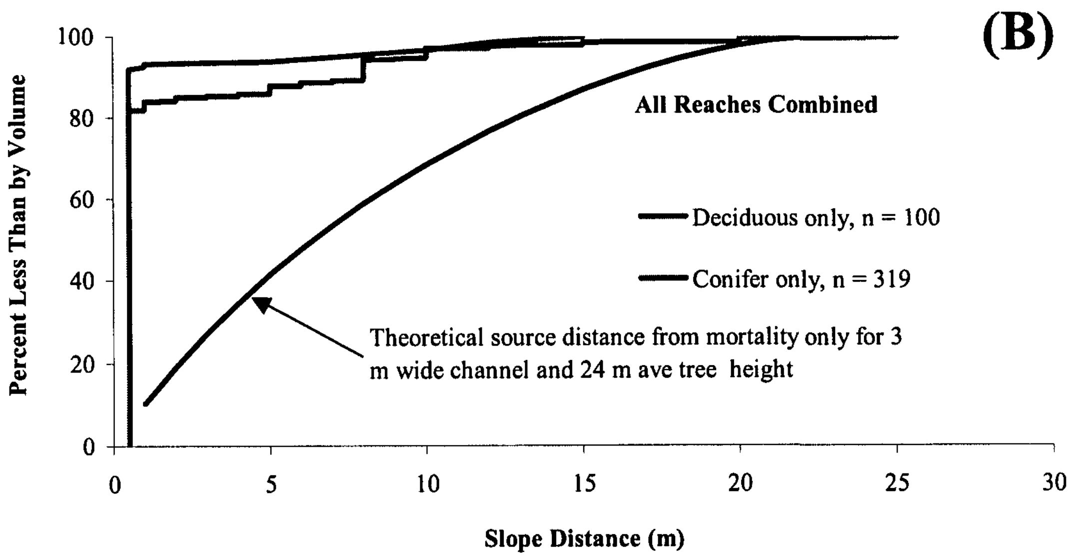


Figure 9 - (A) Slope distance from stream edge to source of wood for individual reaches, and (B) source distance of conifers and deciduous trees for all reaches combined.

4.3 Wood Recruitment Rates

Rates of wood recruitment ($m^3\ km^{-1}\ yr^{-1}$) for chronic mortality, bank erosion, and landsliding were estimated based on the volumes of recruited wood and the weighted mean age of recruited wood in each category (e.g., Equation 5). To calculate age-decay class relationships, we aged 39 pieces of wood in LNF Noyo River. This data was combined with age data from the lower Van Duzen River (Benda et al. 2002a), and the Redwood and Bear Haven Creeks (Campbell Timberland Management 2002) to yield a total of 178 aged pieces. The mean ages were calculated for seven decay classes of conifer and deciduous trees individually and they ranged from 1 to 48 years (unpooled data Table 4). As a result of variable decay rates, several age-decay

Table 4 - Summary age statistics for pooled and unpooled decay classes of recruited large wood. Decay class ages in years were determined from dependent saplings and other field evidence of recruitment age.

Class	Mean	StDev	N	Class	Mean	StDev	N
Conifers							
Needle[a]	1.0	--	--	Needle[a]	1.0	--	--
Twig	4.1	1.5	12	Twig, Branch	5.0	2.4	25
Branches	5.9	2.7	13	Primary, Nub	17.9	15.1	30
Primary Branch	10.0	10.5	15	Hard, Rotten	42.4	27.6	85
Nub	25.7	15.0	15				
Hard	41.2	27.6	70				
Rotten	47.9	27.8	15				
Deciduous							
Leave[a]	1.0	--	--	Leave[a]	1.0	--	--
Twig[b]	4.1	1.5	12	Twig[b], Branch	4.4	1.8	19
Branch	5.1	2.1	7	Primary, Nub, Hard	11.2	6.4	13
Primary Branches	10.0	0.0	2	Rotten	20.5	14.3	8
Nub	9.0	0.0	1				
Hard	11.6	7.3	10				
Rotten	20.5	14.3	8				

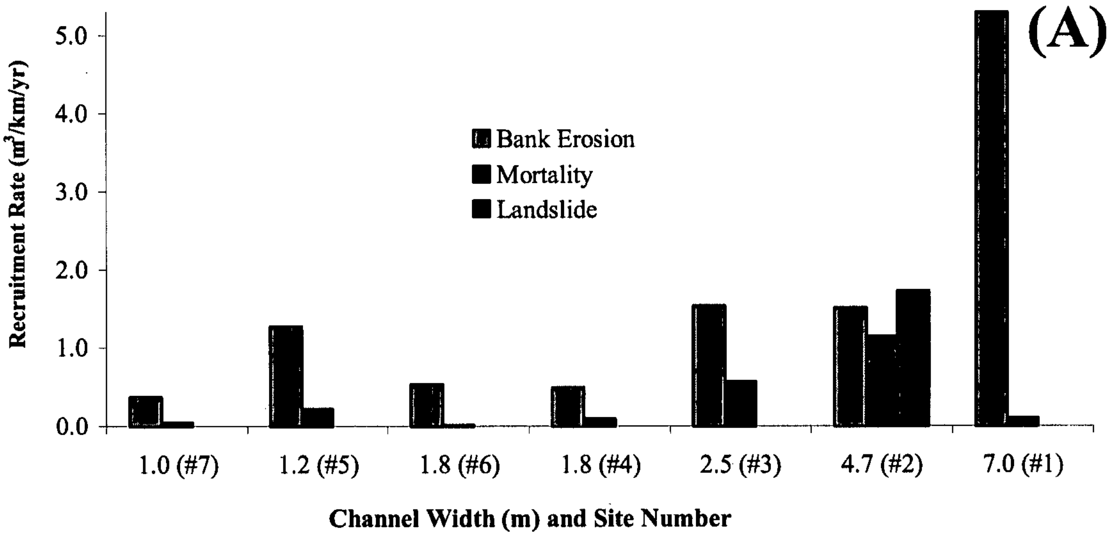
Notes:

a - age of needle and leave decay classes are assumed to be 1 year.

b - twig decay class data was not available for deciduous trees, so conifer data was used as a surrogate.

classes overlapped, which were pooled to create four decay classes that had significantly different mean ages (ANOVA with Tukey HSD comparison between groups, at significance level of 0.2) (pooled data Table 4). This age–decay class relationship was used to assign ages for recruited trees in our surveys where an age could not be determined from field evidence (dependent saplings, adjacent vegetation, etc.). Weighted mean age using Equation 5 for each of the seven study sites are shown in Table 2.

Wood recruitment rates (conifer and deciduous combined) ranged from 0.01 to 1.1 $m^3\ km^{-1}\ yr^{-1}$ (average 0.4) for mortality, 0.4 to 5.3 $m^3\ km^{-1}\ yr^{-1}$ for bank erosion (average 1.6), and 0 to 1.7 $m^3\ km^{-1}\ yr^{-1}$ for landsliding (average 0.2) (Figure 10A, Table 5). Based on the average recruitment rates for all seven sites, bank erosion recruitment dominated (74%), followed by mortality (15 %), and landsliding (12%) (Figure 10B). Recruitment associated with bank erosion showed an increasing rate with increasing width (Figure 10A).



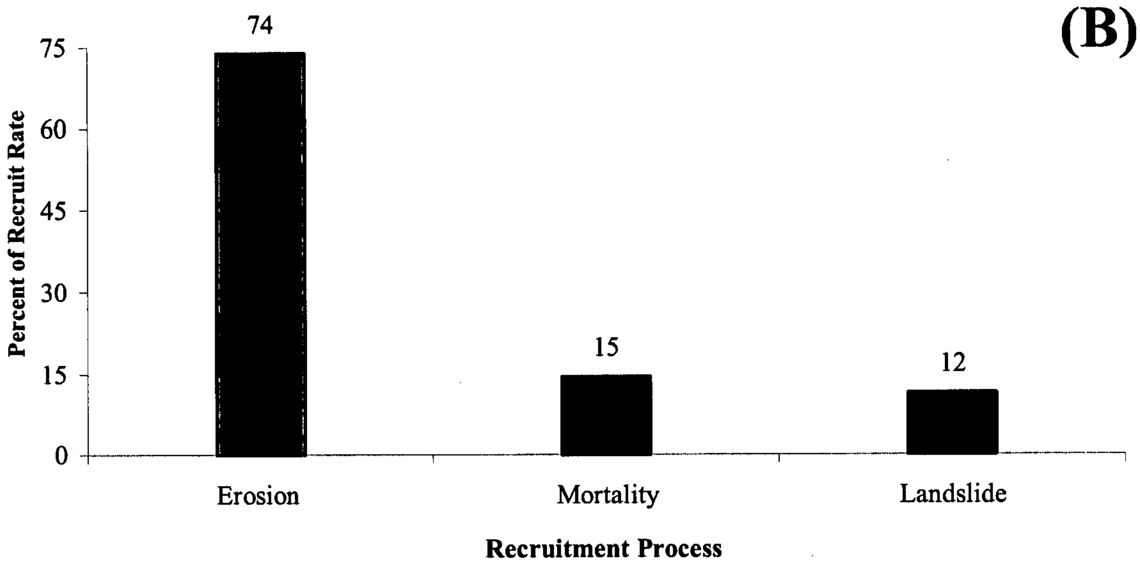


Figure 10 - (A) Wood recruitment rates by process. Horizontal axis shows channel width followed by study site number in parentheses. (B) Percent of recruitment rate by process.

Table 5 - Summary of wood recruitment rates, bank erosion rates, and tree mortality rates.

	Wood Recruitment Rates (m^3/km/yr)						Bank Erosion rates (cm/yr)		Mortality Rates (%/yr)		
Site No.	Erosion	Mortality	Deciduous Mortality	Conifer Mortality	Slide	Total	1 Bank	2 Banks	Total	Deciduous	Conifer
1	5.3	0.1	0.02	0.1	0	5.5	30.7	15.4	0.04	--	0.04
2	1.5	1.1	0.06	1.1	1.7	5.5	7.0	3.5	0.70	0.31	0.39
3	1.5	0.6	0	0.6	0	2.7	7.6	3.8	0.31	0.00	0.31
4	0.5	0.1	0	0.1	0	0.7	18.3	9.1	0.41	--	0.41
5	1.3	0.2	0.002	0.22	0	1.7	30.4	15.2	0.60	0.06	0.54
6	0.54	0.01	0	0.01	0	0.6	2.8	1.4	0.02	0.00	0.02
7	0.38	0.04	0.001	0.04	0	0.5	3.0	1.5	0.12	--	0.12
Averages											
Little NF Noyo	1.6	0.3	0.01	0.3	0.2	2.4	14.3	7.1	0.31	0.09	0.26
Bear Haven	0.4	0.4	0.05	0.4	0.1	1.4	4.7	2.4	0.69	0.43	0.26
Redwood	0.3	0.2	0.09	0.1	0.2	0.9	2.6	1.3	0.88	0.81	0.07
Van Duzen	3.7	4.3	2.1	2.9	2.8	15.8	25.0	13.0	0.83	0.64	0.93
RW Old Growth	3.6	3.9	1.3	2.7	1.1	12.6	2.8	1.4	0.07	0.01	0.06

4.4 Forest Mortality Rates

Forest biomass density in areas adjacent to the wood study sites in LNF Noyo River averaged 515 m^3 ha^{-1} (30 m^3 ha^{-1} deciduous, 515 m^3 ha^{-1} conifers) for all trees over 10 cm in diameter, the minimum piece size inventoried in streams (Table 2) (Campbell Timberland Management 2003, unpublished data). Tree heights averaged 11 m for deciduous and 23 m for conifer species (Table 2). Using these data and estimates of mortality recruitment (Table 5, Figure 10A) that was dominated by conifer trees (Figure 11A), Equation 6 was used to back estimate rates of forest mortality. Conifer mortality rates ranged from 0.01 to 0.6% yr^{-1} and averaged 0.26% yr^{-1} over a period of approximately 42 years (decay class range). Mortality rates of deciduous trees ranged from 0 to 0.31% yr^{-1} (average 0.09% yr^{-1}) over a period of approximately 17 years (Table 5, Figure 11B).

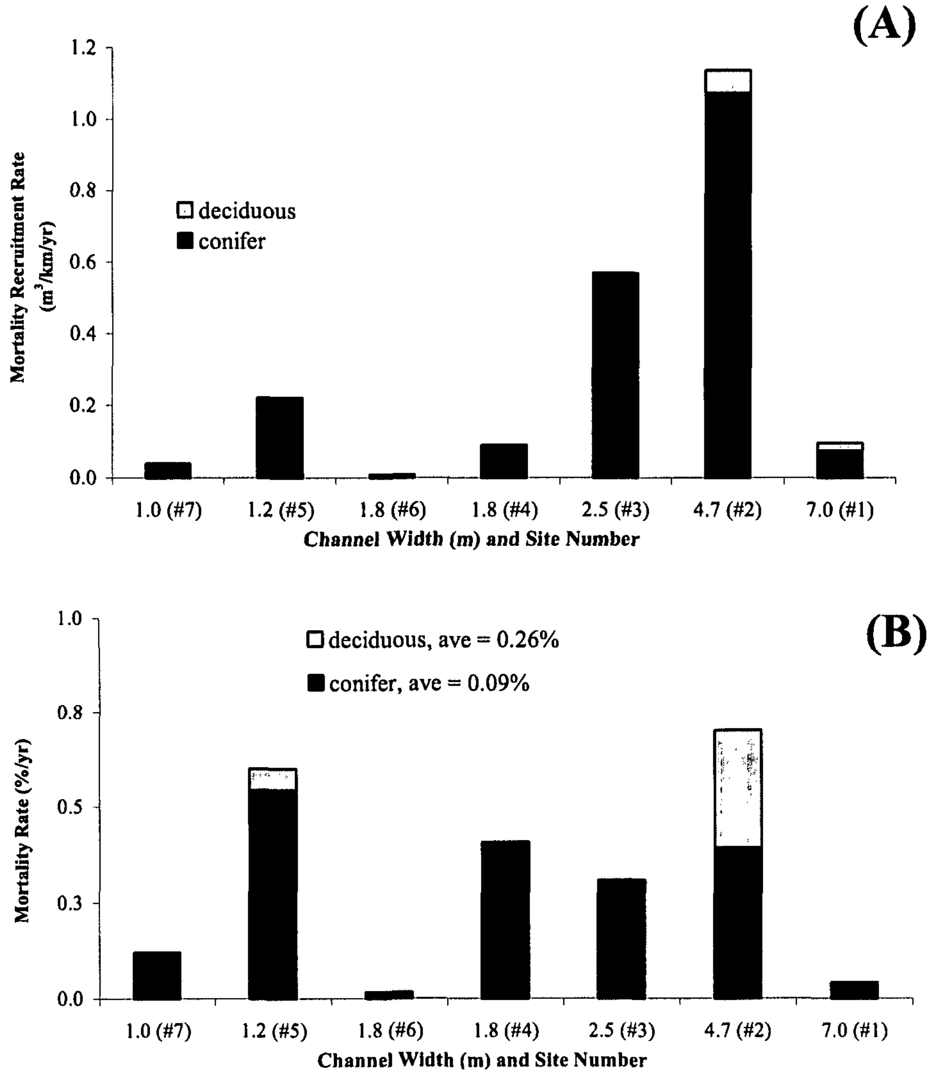


Figure 11 - (A) Wood recruitment rate by mortality for conifer and deciduous trees, and (B) mortality rates for conifer and deciduous trees. Horizontal axis shows channel width followed by study site number in parentheses.

4.5 Bank Erosion Rates and Associated Sediment Budget

Using the measured biomass density along the study reaches (Campbell Timberland Management 2003, unpublished data) and the estimates of bank erosion wood recruitment (Table 5, Figure 10A), Equation 7 was used to calculate rates of bank erosion along the 2nd and higher order study reaches. Because large floods have occurred in northern California during the last decade (U.S. EPA 2000) we report bank erosion values for one and both sides of the channel. Calculated bank erosion rates ranged from 3 to 31 cm yr^{-1} (average 14 cm yr^{-1}) for one bank, and half those rates for two banks (Table 5, Figure 12). The calculated bank erosion rates using Equation 7 varied depending on the mean weighted age used in our analysis (Table 2). The seven study sites used to

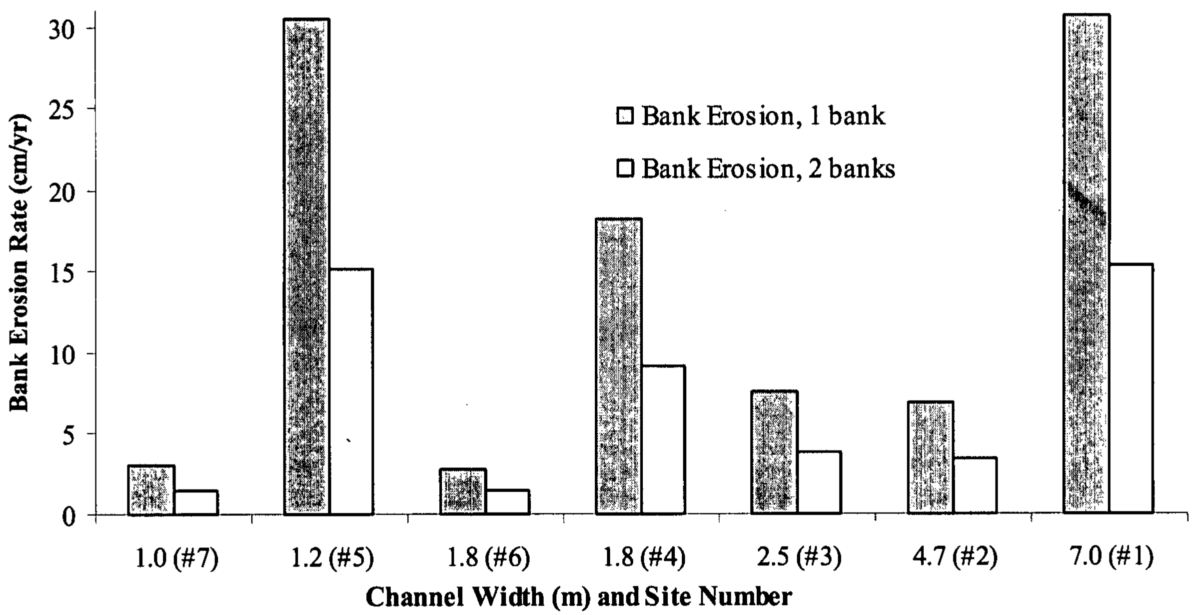


Figure 12 - Bank erosion rates for one and both banks. Horizontal axis shows channel width followed by study site number in parentheses.

estimate an average bank erosion rate had mean weighted ages of wood recruited by bank erosion that varied between 20 and 36 years (28 years average) (Table 2).

Based on field observations, the low order channels appeared to be a major source of sediment and a sediment budget based on bank erosion may be informative for sediment sources within the watershed. Historical legacy logging impacts observed in the LNF Noyo include both (1) first entry logging impacts where most channels were cleaned to ease transportation of timber for hauling in low order channels and splash damming in high order channels, and (2) second entry (tractor) logging impacts from filling both low and high order channels with slash and soil to ease hauling of timber. Lower gradient fish-bearing streams were later mechanically cleaned of wood, often using tractors. These high order channels appear to be incised resulting in steep vertical banks, and the channel is no longer connected with the former flood plain (now a terrace) in most areas. Low order channels were not cleaned of slash and soil, and these channels are incising in many areas creating highly unstable steep banks. Similar observations have been made in Caspar Creek (Dewey et al. 2003), where *"rates of suspended sediment delivery per unit area of* *catchment correlate better with the amount of exposed bank area in reaches upstream of stream gages, than with the volume of sediment delivered by landslide events.*" Bank erosion in higher order channels (3rd and higher) is not included in most sediment budgets because bank erosion on one side of the bank is assumed to be offset by sediment accretion on the opposite bank, necessary to maintain channel width in long-term steady state. Because this equilibrium is not apparent from field observations, we applied our calculated bank erosion rates to the LNF Noyo stream network to estimate a sediment budget from bank erosion and soil creep only. Using the soil creep rate estimated in Bear Haven and Redwood Creek basins (Campbell Timberland Management 2002), soil creep rates averaged 1.9 cm yr^{-1} (both banks) over an average period of 27 years. Using a numerical model (Miller submitted) in conjunction with 10 m digital elevation data, the average drainage density for first order channels was estimated to be 2 km km^{-2}. The upper limits of the drainage network, or channel heads, were estimated using a slope-area threshold for humid temperate basins (Montgomery and Dietrich 1992; Miller submitted). Applying the average soil creep rate along both banks of the 1st order channel network of LNF Noyo Basin yields 76 m^3 km^{-2} yr^{-1} (0.019 m yr^{-1} * 2 banks * 1 m * 2,000 m km^{-2}). Using an assumed dry bulk density of 1600 kg m^{-3} for hillslope material (Benda and Dunne 1987), sediment yield from soil creep is estimated to be approximately 122 t km^{-2} yr^{-1}.

Similarly, the average drainage density for 2nd and higher order channels was estimated to be 1.8 km km^{-2}. Applying the average bank erosion rate of 7.1 cm yr^{-1} (for two banks, Table 5) to the 2nd and higher order channel network of LNF Noyo Basin yields 409 t km^{-2} yr^{-1} (0.071 m yr^{-1} * 2 banks * 1 m * 1,800 m km^{-2} * 1.6 t m^{-3}. Sediment input from landslides was not included in the budget since it was only observed in one reach (Reach #2) and could not be extrapolated to the remainder of the network without additional information. Nevertheless, measurements of landslide characteristics (dimensions, sediment delivery ratio, age, slope, etc.) were obtained in this reach for possible use in future sediment budgets (Appendix A).

4.6 Wood Transport

The wood budget for LNF Noyo River basin did not calculate the flux of wood into and out of study reaches (i.e., $Q_i = Q_o = 0$ in Equation 1). However, several parameters in Equation 9 were estimated to provide some insight into wood transport in the LNF Noyo River basin. Parameters measured included debris jam age, jam spacing, the proportion of channel blocked by jams. These data were used to predict wood transport distances over the life time of wood pieces.

In the LNF Noyo River watershed, the average debris jam age was 30 years with jam age decreasing with increasing drainage area ($R^2 = 0.6$, Figure 13). The distribution of jam spacing in LNF Noyo River ranged from 24 to 110 m (average 73 m), and showed a weak increasing trend with drainage area ($R^2 = 0.3$, Figure 13). The percentage of channel blocked by a jam in the LNF Noyo River ranged from 62 to 100% (average 90%), and showed a decreasing trend with drainage area ($R^2 = 0.84$, Figure 13). Using Equation 9 and an assumed lifespan of wood in streams of 100 years (i.e., using a 3% yr^{-1} wood decay rate, Benda and Sias 2003), the predicted average transport distance ranged from 57 to 1311 m and averaged 442 m. The predicted transport distances increased with increasing channel size and drainage area ($R^2 = 0.6$, Figure 13).

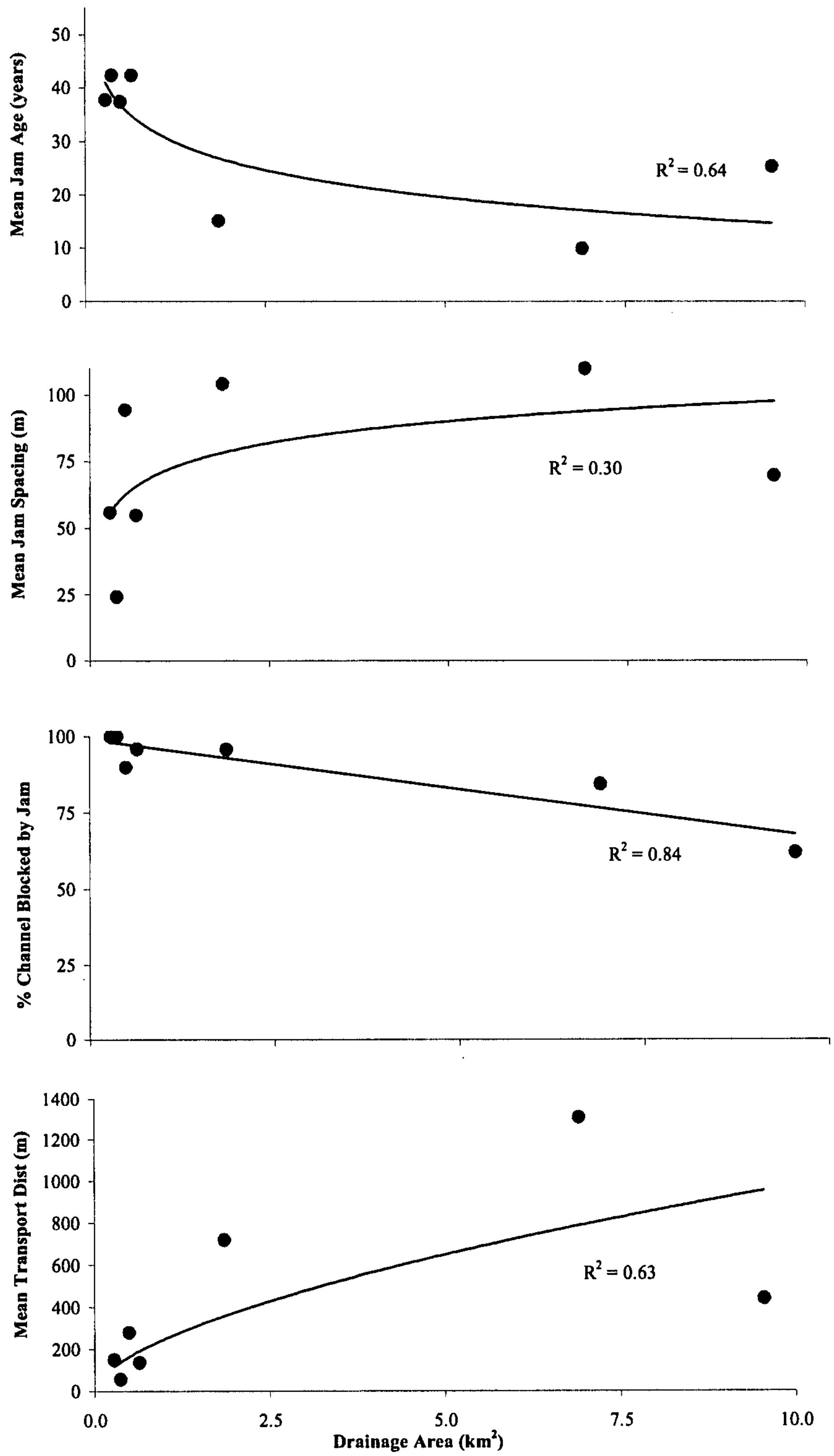


Figure 13 – Attributes of wood transport plotted against drainage area including (from top to bottom) jam age, jam spacing, percentage of channel blocked by jam, and predicted lifetime wood transport using Equation 9 and the data shown in the top three figures.

5. Discussion

5.1 Differences Between LNF Noyo River, Bear Haven Creek, and Redwood Creek Basins

There are many similarities in wood recruitment and transport between the LNF Noyo River and previous wood budgets performed in the Bear Haven and Redwood Creek basins (Campbell Timberland Management 2002). However, there are also important differences between the three basins in the numerical values of various parameters. For example, although non-mortality sources of wood dominate in all three basins, the rates of wood recruitment from bank erosion in LNF Noyo River were 75 to 81 percent higher than Bear Haven and Redwood Creeks (Table 6). In addition, there was a higher proportion of older wood in LNF Noyo that could not be identified with a recruitment source or logging related (Table 6).

Table 6 - Comparison of wood budget parameters for Bear Haven Creek, Redwood Creek, and LNF Noyo River.

Attribute	LNF Noyo	Bear Haven	Redwood
Wood Storage (m^3/100m)			
range	2 - 95	47 - 67	0.9 - 48
mean	18	22	18
% Pieces identfied by Source	26	66	56
% Logging Related (by volume)	19	55	76
Source Distance (feet)			
60%	2	16	10
80%	2	40	49
Wood Recruitment (m^3/km/yr)			
Mortality	0.3 (15%)	0.4 (44%)	0.2 (29%)
Bank Erosion	1.6 (74%)	0.4 (44%)	0.3 (46%)
Landslide	0.2 (12%)	0.13 (14%)	0.17 (25%)
Forest Biomass (m^3/Ha)			
Conifer	485	301	504
Deciduous	30	32	34
Mortality Rates (%/yr)			
Conifer	.09	0.26	0.07
Deciduous	.26	0.4	0.8
Bank Erosion Rates - 1 bank (cm/yr)			
range	3 - 31	1 - 11	1 - 8
mean	14	5	3
Mean Jam Age (years)	25	42	35
Mean Jam Spacing (meters)	79	54	59
Mean Wood Transport Dist. (meters)	442	155	464

Because of the dominance of wood recruited by bank erosion in LNF Noyo River, distances to sources of wood were shorter than those in Bear Haven and Redwood Creeks (Table 6). However, where landslides do occur in the LNF Noyo River (e.g., Reach #2), source distances are further than other reaches but still less than predicted by mortality alone (Figure 9A). Predicted wood transport in the LNF Noyo River is similar to that predicted in Redwood Creek, despite differences in mean jam age and spacing (Table 6).

In summary, the wood budget conducted in the LNF Noyo River reinforces and expands upon observations from previous wood budgets in Bear Haven and Redwood Creeks (Campbell Timberland Management 2002) and other regions (e.g., Martin and Benda 2001; Benda et al. 2002a) that have important implications for management of riparian forests, specifically: (1) wood storage is highly variable within and across stream reaches, (2) wood recruitment is generally dominated by processes other than mortality (i.e., bank erosion), (3) source distances are fundamentally influenced by the dominant recruitment process and in the case of the LNF Noyo significantly less than that predicted for mortality, and (4) recruitment of wood that forms jams (key pieces) is dominated by bank erosion.

5.2 Spatial Variability of Wood Storage: Implications for Monitoring

Similar to Bear Haven and Redwood Creek basins, the wood budget in the LNF Noyo River revealed a large range of spatial variability in total wood storage and recruited wood (Figure 4). Variation is driven by both a diversity of recruitment processes and by historical logging debris that affected total wood volumes. The observed spatial variability in recruited wood (excluding logging debris) is driven by variation in topography that governs localized bank erosion and streamside landsliding, and by variation in forest mortality.

There is increasing interest in setting targets for wood storage and conducting monitoring in California (e.g., Pacific Lumber Company [PALCO] 1998), however, there are no current monitoring guidelines or inventory protocol (e.g., Overton et al. 1997, Schuett-Hames et al. 1999) that consider spatial and temporal variability in wood recruitment. Given the observed spatial variability in wood volumes, a pertinent question is: over what distance of channel should wood inventories be conducted to estimate mean values? A cumulative spatial average of total and recruited wood storage per 100 m reaches is plotted for the LNF Noyo River to determine how mean values are affected by survey distance. Although a continuous survey reach would be optimum to evaluate this question, we joined our discontinuous surveys to illustrate the degree of spatial variability encountered in the LNF Noyo River basin (Figure 14). Because of high spatial

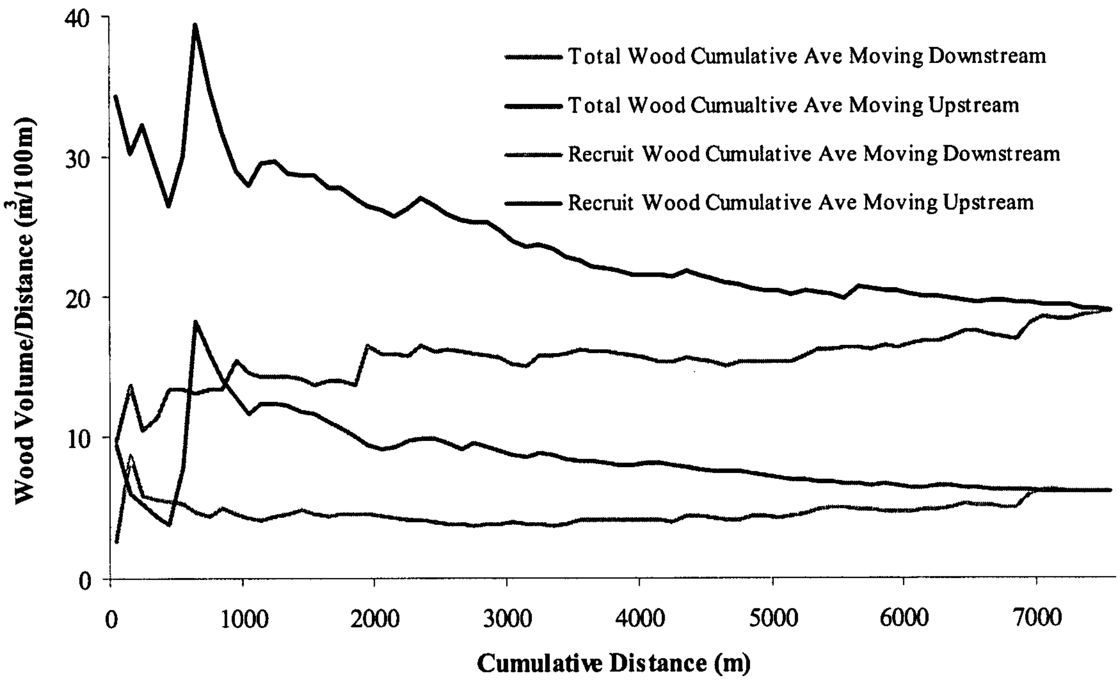


Figure 14 - Cumulative average of total wood storage and recruited wood. Reach data are plotted from largest to smallest streams (i.e. moving upstream) and from smallest to largest streams (i.e. moving downstream).

variation in both total (standard deviation $\sigma = 15$ m^3/100m) and recruited wood ($\sigma = 10$ m^3/100m), wood storage did not converge on a stable mean value over the entire survey length of 7.6 km, nor were there major differences in variation of wood volumes when moving either up or downstream. In contrast, spatial variability of wood storage in Redwood Creek was lower (total wood $\sigma = 11$ m^3/100m, recruit wood $\sigma = 4$ m^3/100m) and stable mean values of total wood storage converged at approximately 4 km of continuous surveys. Depending on the degree of variability driven by differences in bank erosion, landsliding, forest mortality, and logging history, it might be infeasible to obtain an accurate mean value of wood storage. In addition, the history of storms and floods will strongly influence variability in storage. This suggests that monitoring total wood storage may be an ill advised strategy.

5.3 Disturbance-Related Wood Recruitment: Implications for Regulations

Existing wood recruitment models consider wood input from mortality only (Bragg et al. 2000, Welty et al. 2002) and none of the current regulatory approaches considers recruitment from other processes (i.e., bank erosion, landsliding, etc.), and hence the role of disturbances in wood recruitment. This study, previous wood budgets in Redwood and Bear Haven Creeks, and budgets in other regions (Martin and Benda 2001; Benda et al. 2002a) reveal that wood recruitment is often dominated by sources other than mortality, including in unmanaged areas. For example, in the LNF Noyo River, wood recruitment is dominated by bank erosion (81% by volume), and when combined with streamside landslides and debris flows, 89% of wood comes from non-mortality sources, while 11% originates from forest mortality (Figure 5B). This result, however, should be conditioned by the elevated high bank erosion rates encountered in the LNF Noyo River that is likely due to historical logging activities (see section 5.7 below). In channels with lower bank erosion rates (a condition that may have existed in the Noyo River watershed with no history of intensive logging), bank erosion recruitment of wood should be proportionally lower leading to proportionally higher wood recruitment rates by other processes, including forest mortality.

The present-day high proportion of wood from non-mortality wood sources in all study areas indicates that wood recruitment is driven largely by disturbance processes, such as storms and floods. Therefore significant variation in total wood storage and wood recruitment should be expected since floods that govern bank erosion and storms that trigger landsliding and blow down occur episodically over time. This provides yet another caveat when constructing wood loading targets and monitoring programs to verify compliance. Although spatial variability in wood storage was evaluated (Figure 14), temporal variability in wood storage was not but it would be expected to contribute to large fluctuations in wood storage, including spatially averaged values. Temporal fluctuations in wood storage could comprise either positive or negative departures from a long-term (century-scale) mean values (U.S. Forest Service 2002; Benda and Sias 2003).

5.4 Distances to Sources of Wood: Implications for Buffer Strip Design

Recruitment patterns of wood are typically used to design buffer strip dimensions. However, field and modeling research on source distance curves have generally focused on recruitment by forest mortality and hence tree height is often of primary concern when creating the width dimension of buffer strips. The dominance of non-forest mortality sources of wood recruitment in the LNF Noyo River (Figures 5B and 10) and other studies (e.g., Campbell Timber Land Management 2002, Benda et al.2002a) indicate that other factors dictate the width of buffer strips. For instance, in LNF Noyo River, source distance curves are tightly controlled by recruitment process. In most reaches bank erosion dominates (Table 3, Figure 5B, Appendix B), empirical source distance curves are less than the theoretical prediction from mortality only (Figure 9).

5.5 Rates of Forest Mortality, Landsliding, and Bank Erosion: Implications for Predicting Wood Loading

To understand changing wood storage over time and the role of various land use practices, it might be valuable to predict historical and future trends in large wood. However, wood recruitment models typically focus on recruitment by forest mortality (Welty et al. 2002). The wood budget for LNF Noyo River basin indicates that non-mortality sources of wood (i.e., bank erosion and mass wasting) dominate wood recruitment (Figure 5B); bank erosion and landsliding accounted for 89% of all wood recruitment. To construct models that account for all recruitment processes, it is necessary to parameterize rates of bank erosion and landsliding, as well as forest mortality. The rates reported here for all three processes could be used to forecast the changing storage of wood in streams using numerical simulation models.

5.6 Fluvial Transport of Wood: Where Is Movement of Wood Significant?

In the LNF Noyo River basin, ages of wood jams decreased with increasing drainage area (Figures 13) indicating a decreasing stability of jams with increasing channel size. In addition, the distance between jams weakly increased with drainage area, a pattern expected if jam longevity decreases with channel size (Figures 13). Consequently, wood transport (using Equation 9) over the lifetime of wood in streams (~100 years using a 3% annual decay rate) is predicted to vary from less than 100 m in the smallest channels (drainage area of < 1.5 km^2) to several hundred meters at drainage areas of 2 to 10 km^2 (Figure 13).

Predicted wood transport suggests that in small, headwater streams that have drainage areas less than about 1 km^2, wood located in approximately the first 200 meters upstream from the confluence contributes to the wood storage of larger, fish-bearing streams. Because of the predicted short travel distances of wood, the majority of headwater streams will have little wood in transport and hence contribute little wood to larger, fish bearing streams. In larger, fish-bearing streams, wood transport may range from several hundred to over 1000 meters.

5.7 Legacy Effects of Past Harvest and Accelerated Sediment Yield From Bank Erosion

Legacy effects of historical logging activities on erosion rates and sediment yields in the Noyo River watershed, and the LNF Noyo in particular, are relevant to present day forest management because EPA uses sediment budgets as a regulatory tool (e.g., TMDL process) to define background erosion rates and so-called "allowable sediment loads" (U.S. EPA 1999). As one check on the accuracy of the TMDL for the Noyo River (U.S. EPA 1999), including the LNF Noyo, the bank erosion rates estimated during the LNF Noyo wood budget are compared to bank erosion rates contained in the Noyo River TMDL. The so-called "desk top" sediment budget constructed for the Noyo River (GMA 1999) for EPA (i.e., which involved little field work) applied estimates of fluvial bank erosion obtained from "*C. Surfleet (pers. Comm. 1999)*" and "*USDA (1972).*" The sediment yield attributed to bank erosion for the Noyo River TMDL was 200 tons mi^{-2} yr^{-1} (77 tons km^{-2} yr^{-1}). The bank erosion component of the Noyo River sediment budget comprised approximately 43% of the total estimated erosion rate for the period 1933 to 1957 of 470 tons mi^{-2} yr^{-1}.

Disregarding the calculated soil creep inputs from headwater channels (i.e., 1st- and 2nd-order streams with a drainage density of 2 km km^{-2}, the wood budget of the LNF Noyo River estimated fluvial bank erosion rates for third- and higher order channels (having a drainage density of 1.8 km km^{-2}) of 410 tons km^{-2} yr^{-1}. Hence, the LNF Noyo *field estimated* bank erosion rate is significantly greater (~500%) than the 77 tons km^{-2} yr^{-1}estimated in the EPA Noyo River TMDL (U.S. EPA 1999) based on the sediment budget of GMA (1999). Field observations in the LNF Noyo during the wood budget indicated widespread bank erosion and channel incision, a likely consequence of accelerated sediment inputs into the channel during historical logging (prior to 1970), a legacy which may have included burial of channels with sediment and wood for log hauling purposes. This legacy effect of historical logging is the probable cause of the relatively high rates of bank erosion measured during the wood budget in the LNF Noyo (i.e., 7 – 14 cm yr^{-1}). The likelihood for underestimating erosion rates (because of the "desk top" approach) in the EPA-funded sediment budget in the Noyo River was acknowledged by GMA (1999) and the U.S. EPA (1999). Nevertheless, the Noyo River TMDL states that the 200 tons mi^{-2} yr^{-1} (77 tons km^{-2} yr^{-1}) bank erosion rate "is likely an *overestimate* but it is based on reasonably good data collected by the Mendocino Redwood Company and is the best available information." The conclusion that sediment input or sediment yield rates in the Noyo River sediment budget (GMA 1999) are significantly underestimated was also reached by Koehler et al. (2002) who speculated that in the Noyo River "remobilized historic sediment [...due to large volumes of sediment delivered to channels in response to past logging activities...] appears to increase suspended sediment load and may be a significant, unrecognized sediment source."

In the Noyo River TMDL (U.S. EPA 1999), bank erosion is considered part of the "background" sediment loading rate and it comprises approximately 54% of the total estimated background of 370 tons mi^{-2} yr^{-1}. Using our field-estimated bank erosion rate of 410 tons km^{-2} yr^{-1} (equivalent to approximately 1060 tons mi^{-2} yr^{-1}), the EPA TMDL may have underestimated the background sediment loading by approximately 250%. Although this analysis may be considered preliminary and possibly deserving of more analytical attention, it suggests that the EPA TMDL for the Noyo River is inaccurate and quantitative values obtained from it should be treated with caution and potentially not used to establish rigorous quantitative thresholds for monitoring or other related activities.

6. Potential Errors and Limitations

There are several potential sources of errors that can affect the estimated rates of wood recruitment. Recruitment rate is governed by our estimates of mean weighted ages and the storage volume of recruited wood. Because there is a lag time between the time of wood recruitment and establishment of saplings, and because near stream vegetation is vulnerable to removal by stream flow, the age of saplings may underestimate the true age of recruited trees. This error would cause an overestimation of wood recruitment rate, an error that may increase with increasing channel size because of the increased potential of flow disturbances in larger channels. The absolute magnitude of these errors is uncertain given our small data set. Our method of calculating mean age of recruited wood (Equation 5), however, will tend to compensate for this potential error, since it provides greater weight to older trees.

Care should be taken when extrapolating our results to other basins in northern California or to other regions. In other watersheds, landsliding may be more, or less, important than what we found depending on topography and the connectivity between hillslopes and channels. In addition, the stand-average fraction that becomes in-channel wood may vary in streams that are bounded by steep hillslopes. Nevertheless, the general tendencies revealed in our data combined with similar results from wood budgets in other locales, suggests that overall patterns of wood recruitment could be extrapolated to other locations.

7. Conclusions

Forest land managers are increasingly asked by regulatory agencies and others to craft forest management strategies in accordance with the best available science. The rush to place science in a referee position in management and regulatory conflicts begs the question of the availability and accuracy of science to answer watershed questions (Benda et al. 2002b). There are increasing calls to establish regulatory measures (usually single values) for attributes such as wood storage in streams, erosion, and fine sediment levels (e.g., U.S. EPA 1999).

The wood budget constructed in the LNF Noyo River basin represents an effort by Campbell Timberland Management to obtain better, more site specific scientific information from which to base management decisions upon and possibly to defend against challenges to management strategies. The results from the 7.6 km of detailed channel surveys provides new information from which to considered wood recruitment to streams. For example, although most regulatory policies are fashioned along a mortality-centric view, the field study contained in this report indicates that the majority of wood originates from non-mortality sources, specifically bank erosion. Another outcome of this study is the documentation of significant spatial variation in wood storage, partly driven by spatial variation in the dominant recruitment processes, including bank erosion and streamside landsliding. The high degree of spatial variability documented in LNF Noyo River basin questions the efficacy of developing wood loading targets and monitoring programs to verify compliance.

Finally, this study provides some numeric estimates of key parameter values that would be necessary to develop stochastic models of watershed processes, including wood recruitment, wood transport, and sediment production. Such models can be used to examine and illustrate long-term trends (forecasting and backcasting) and the generally unpredictable and stochastic behavior of watershed, such as the LNF Noyo watershed (e.g., U.S. Forest Service 2002).

Appendix A

STREAMSIDE LANDSLIDE INVENTORY

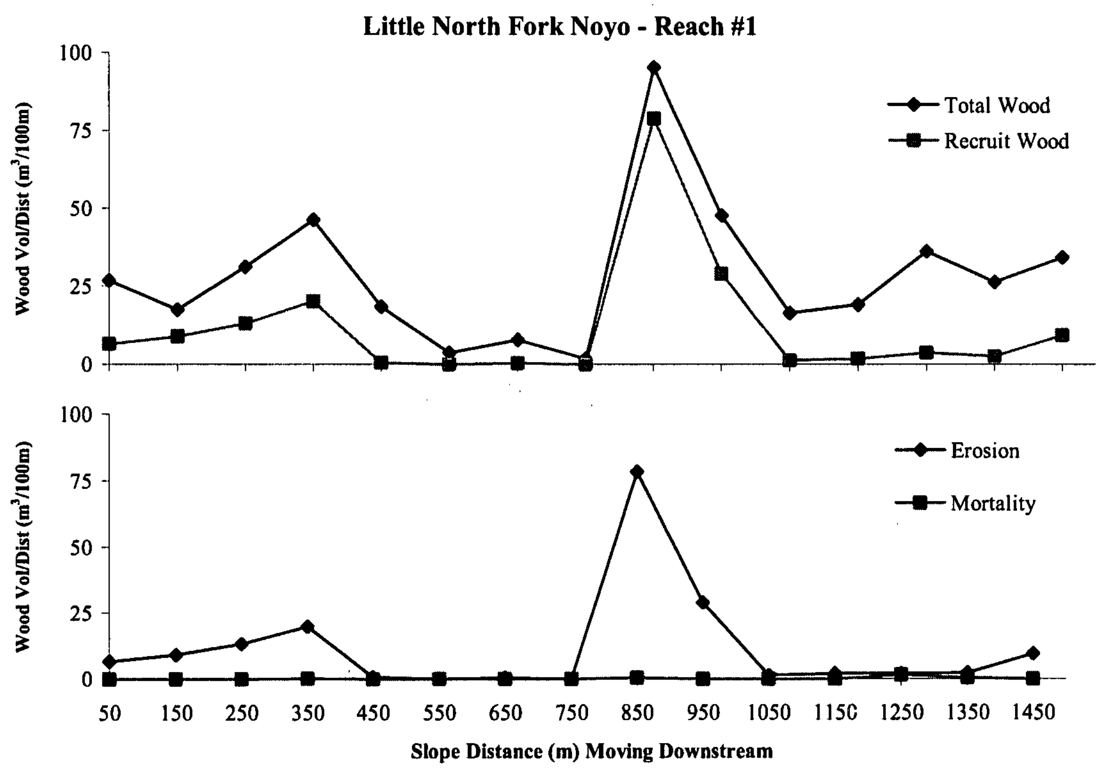
For any future sediment budget estimates, the dimensions of all streamside landslides along study reaches were measured using an inclinometer and tape, including the average length, width, and depth of the landslide scarp, and the hillslope angle. In addition, the percent of sediment delivered to the stream was visually estimated and the approximate age of the slide was determined by dating vegetation within the scarp of the slide by counting branch nodes or using an increment borer or saw and counting tree rings. Streamside landslides were only observed in Reach #2. A massive debris flow (i.e. channel filling) that was partially reactivated recently was observed in Reach 3, however, the volume could not be accurately estimated.

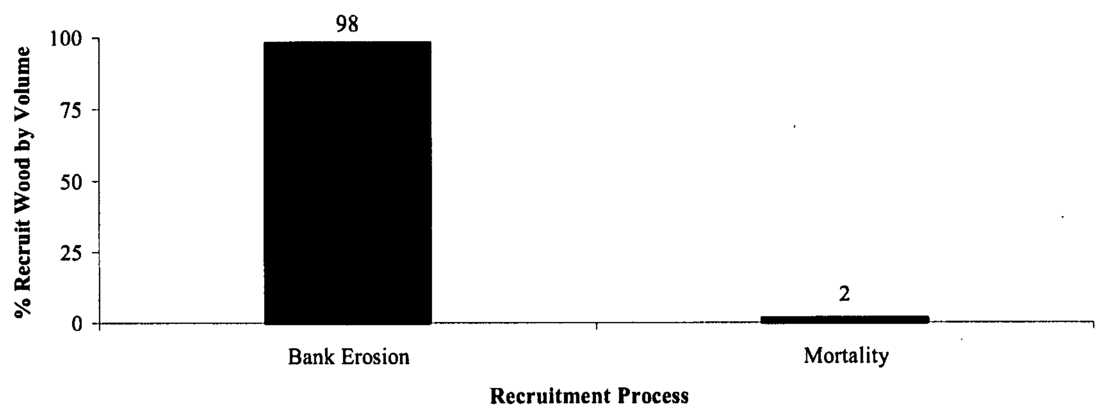
Streamside Landslide Inventory
Slides were only observed in Reach #2 (2.5 km reach length)

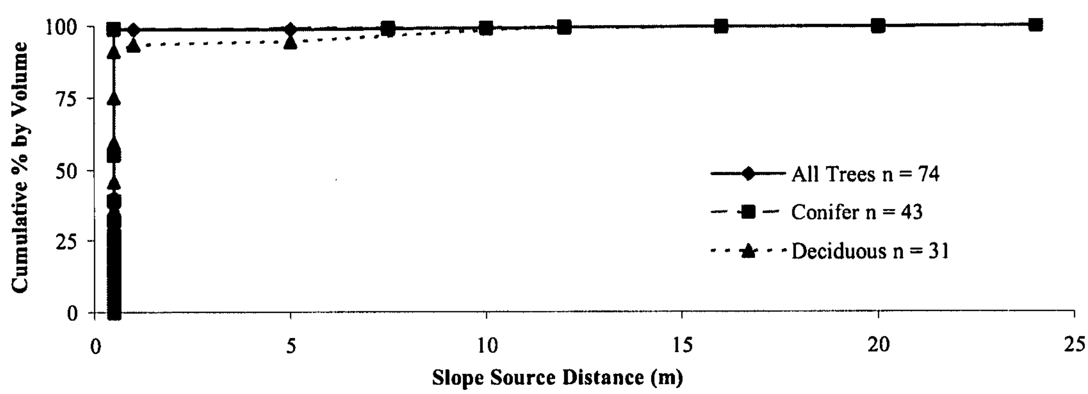
	width (m)	depth (m)	length (m)	hillslope (%)	% delivered	age (yrs)	volume delivered (m^3)
	12	1.5	8	40	70	2	101
	15	2.5	10	33	80	36	300
	5	1.5	15	33	20	3	23
	10	3	8	--	80	42	192
	10	3	8	33	80	5	192
	10	2	8	35	90	14	144
ave:	10	2	10	35	70	17	159

SUMMARY OF WOOD DATA BY INDIVIDUAL REACH

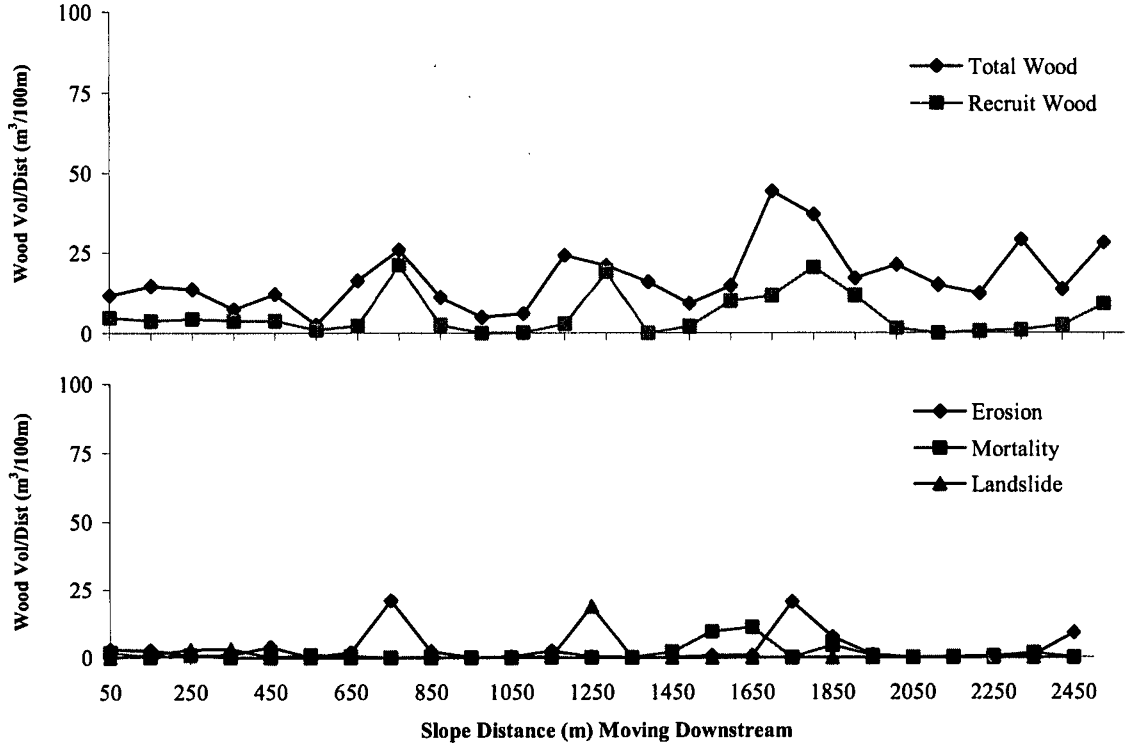
LITTLE NORTH FORK NOYO BASIN

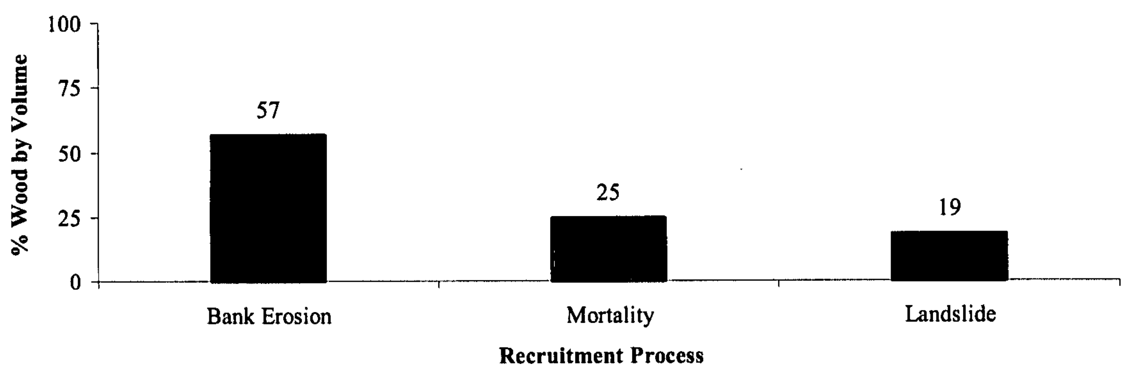

Little North Fork Noyo - Reach #1
Wood Vol/Dist (m^3/100m)
Total Wood
Recruit Wood
Erosion
Mortality
50 150 250 350 450 550 650 750 850 950 1050 1150 1250 1350 1450
Slope Distance (m) Moving Downstream

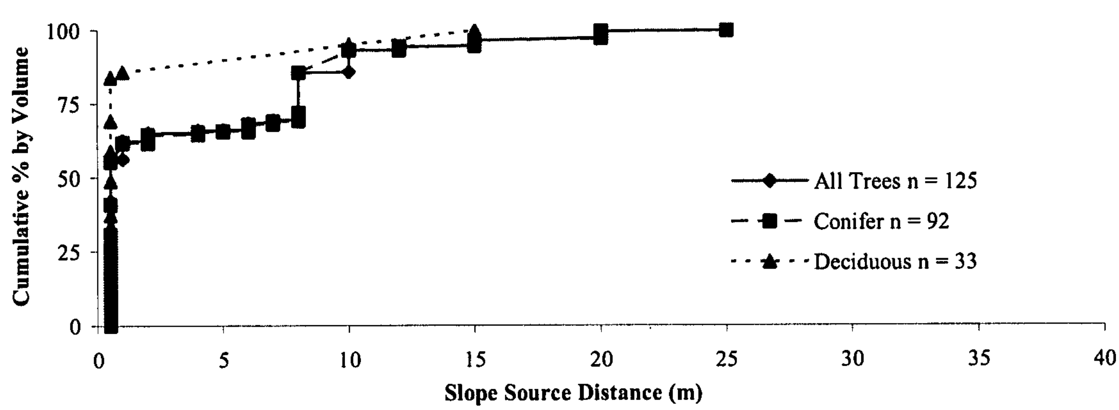

% Recruit Wood by Volume
98
2
Bank Erosion
Mortality
Recruitment Process


Cumulative % by Volume
All Trees n = 74
Conifer n = 43
Deciduous n = 31
Slope Source Distance (m)

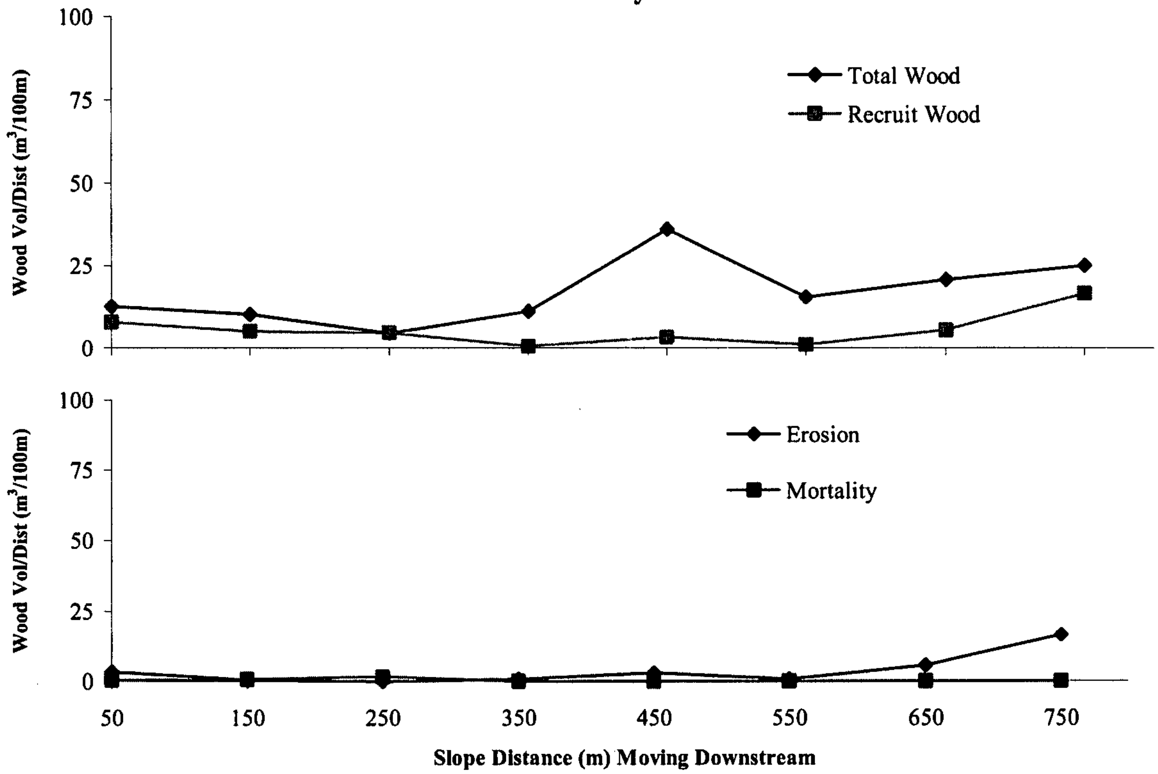
Little North Fork Noyo - Reach #2

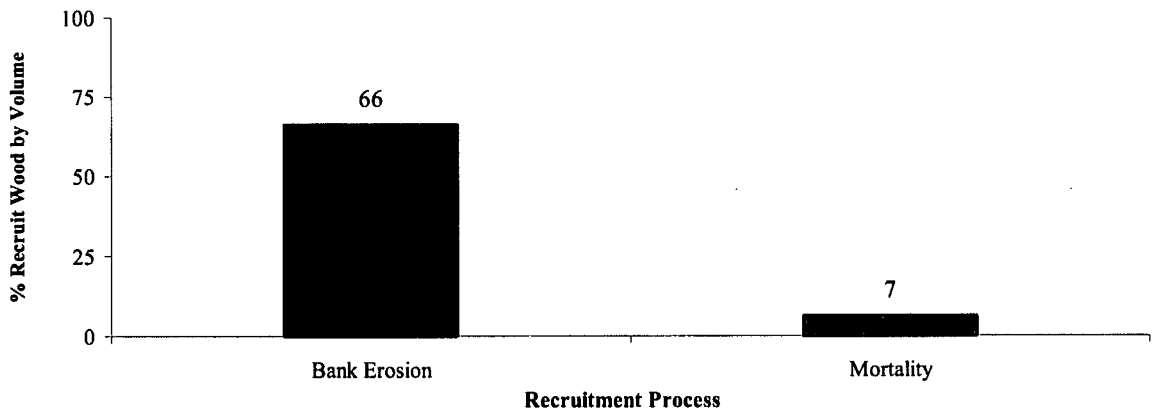


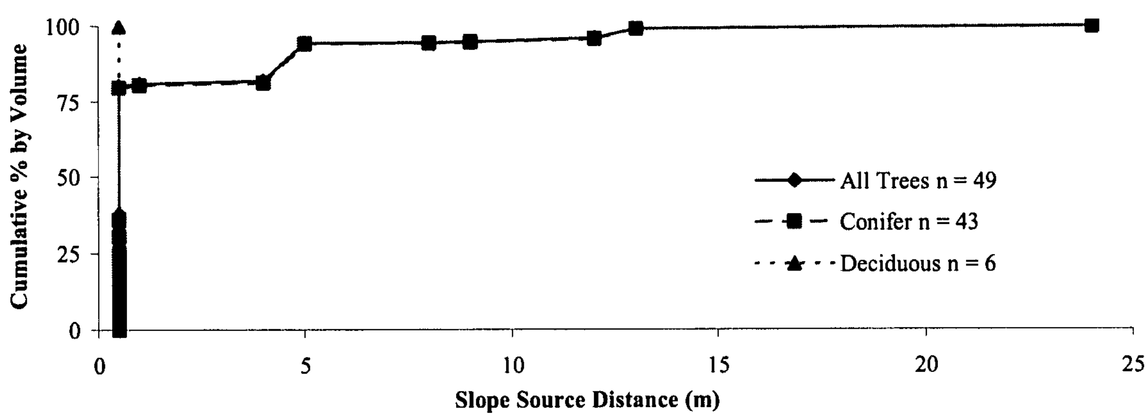




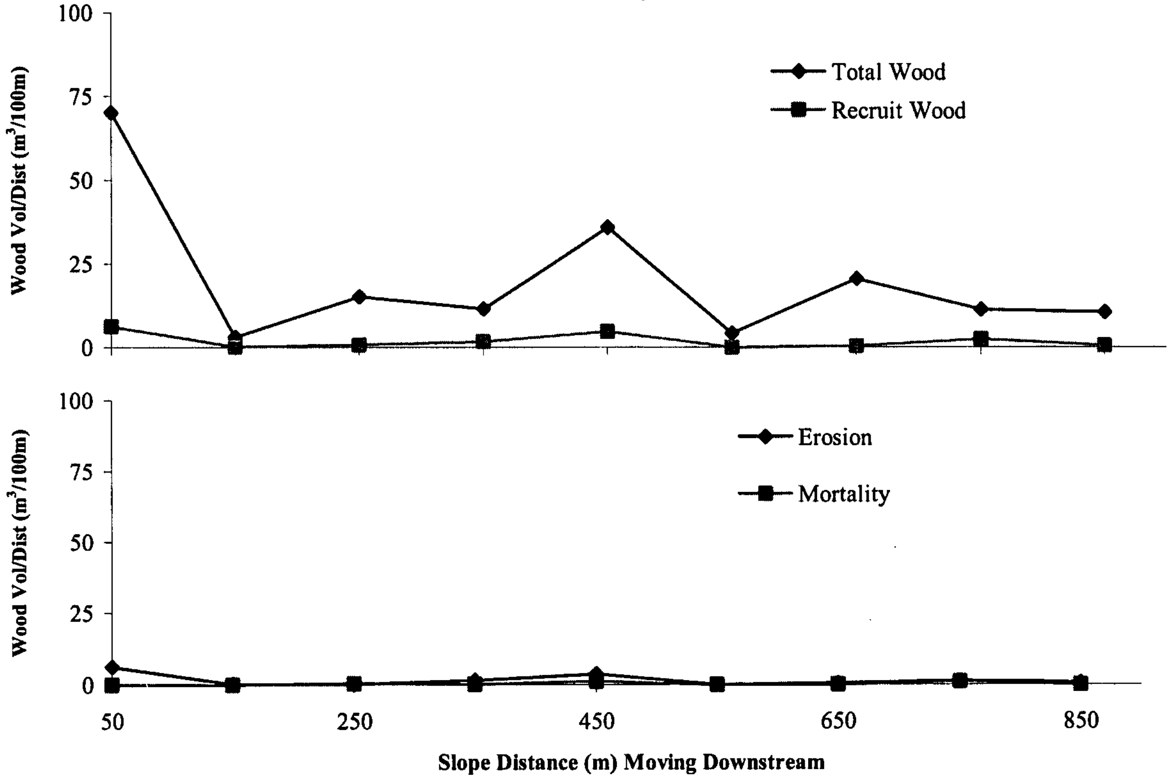
Little North Fork Noyo - Reach #3

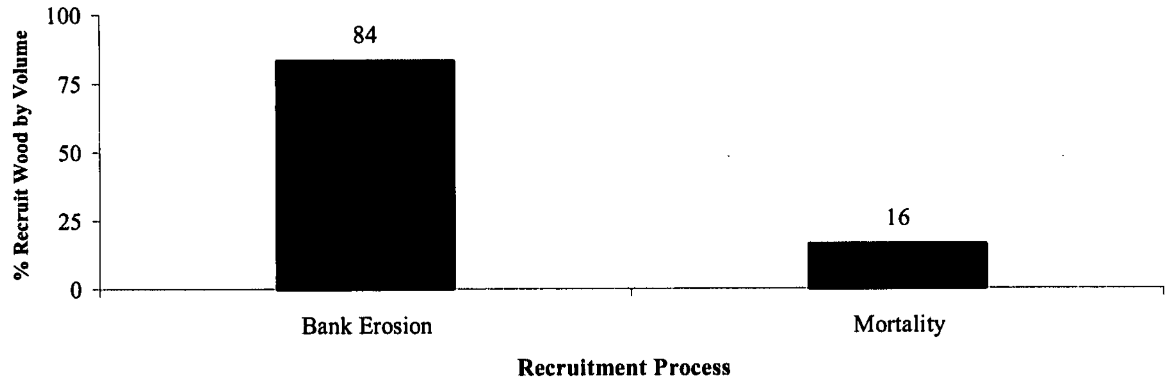


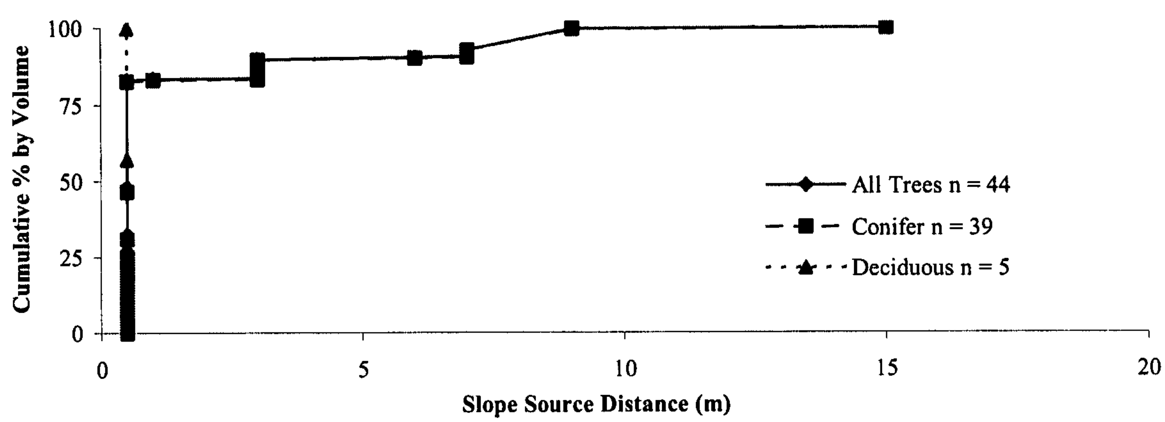




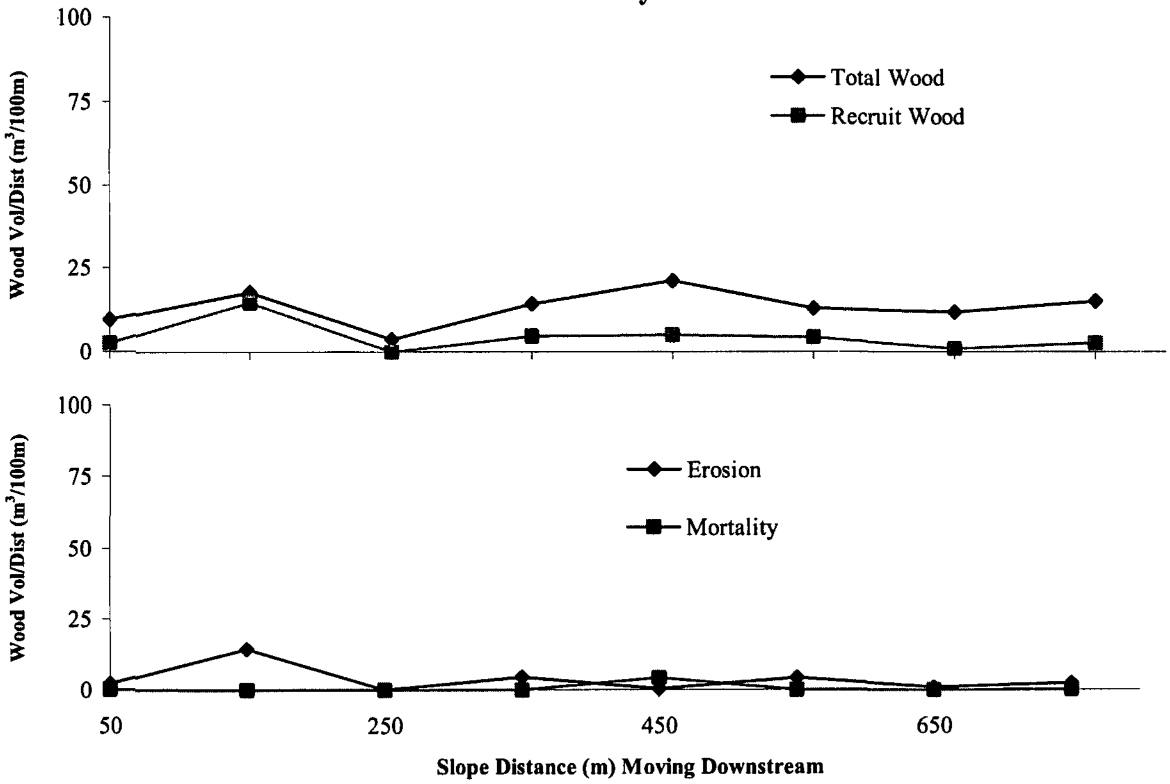
Little North Fork Noyo - Reach #4

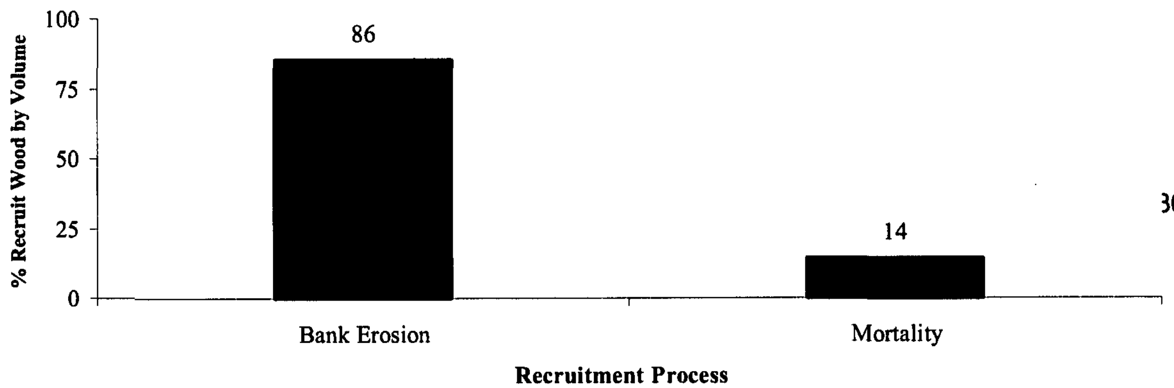


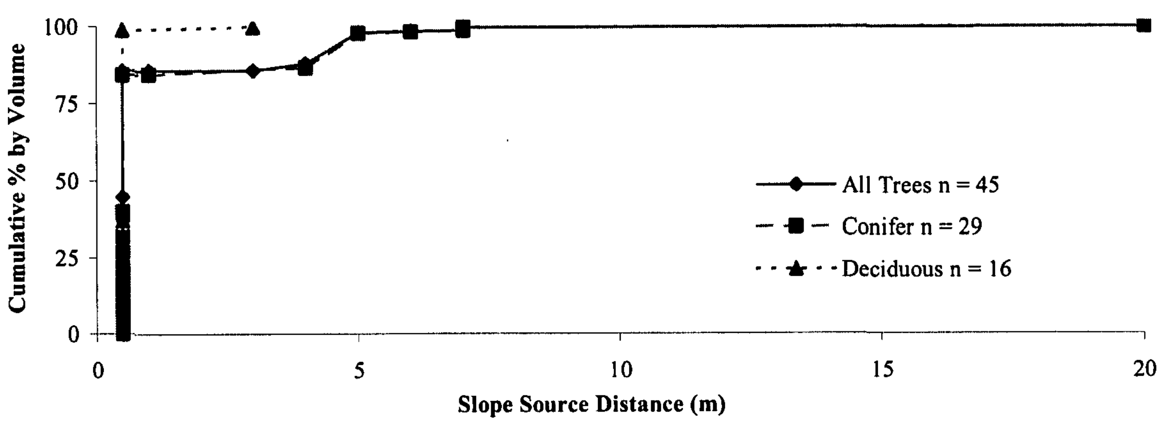




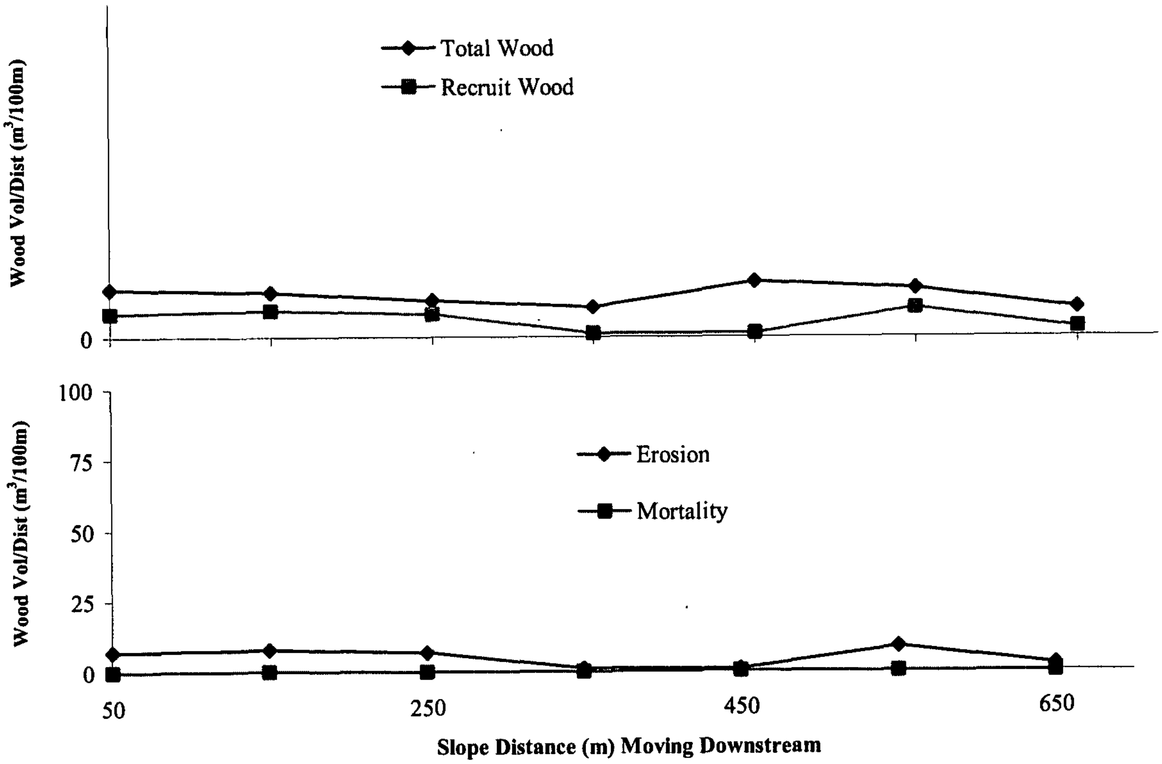
Little North Fork Noyo - Reach #5

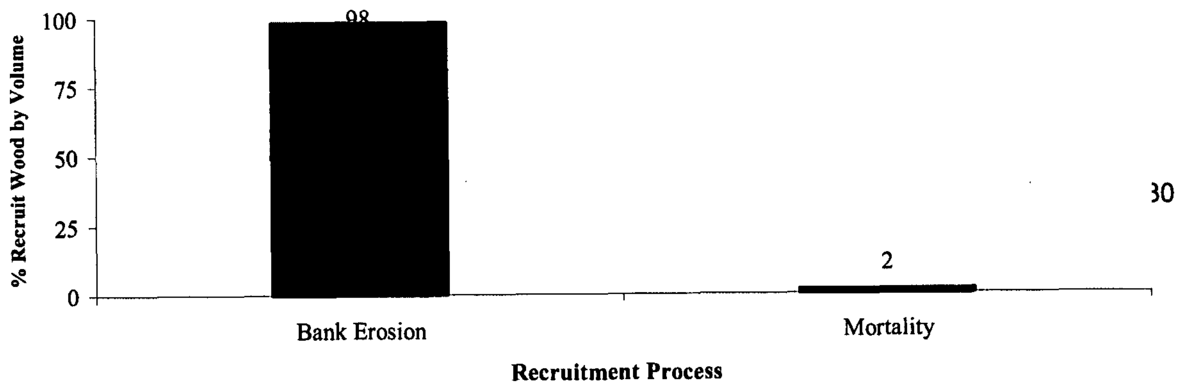


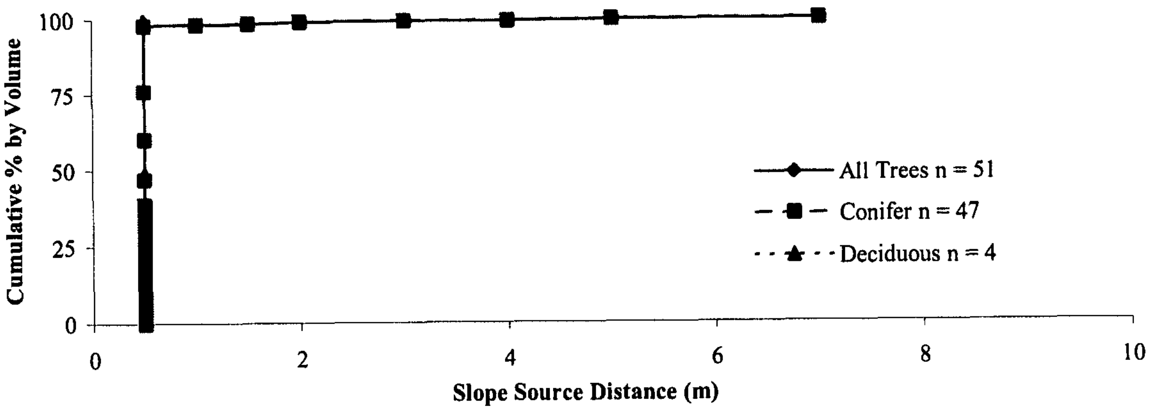




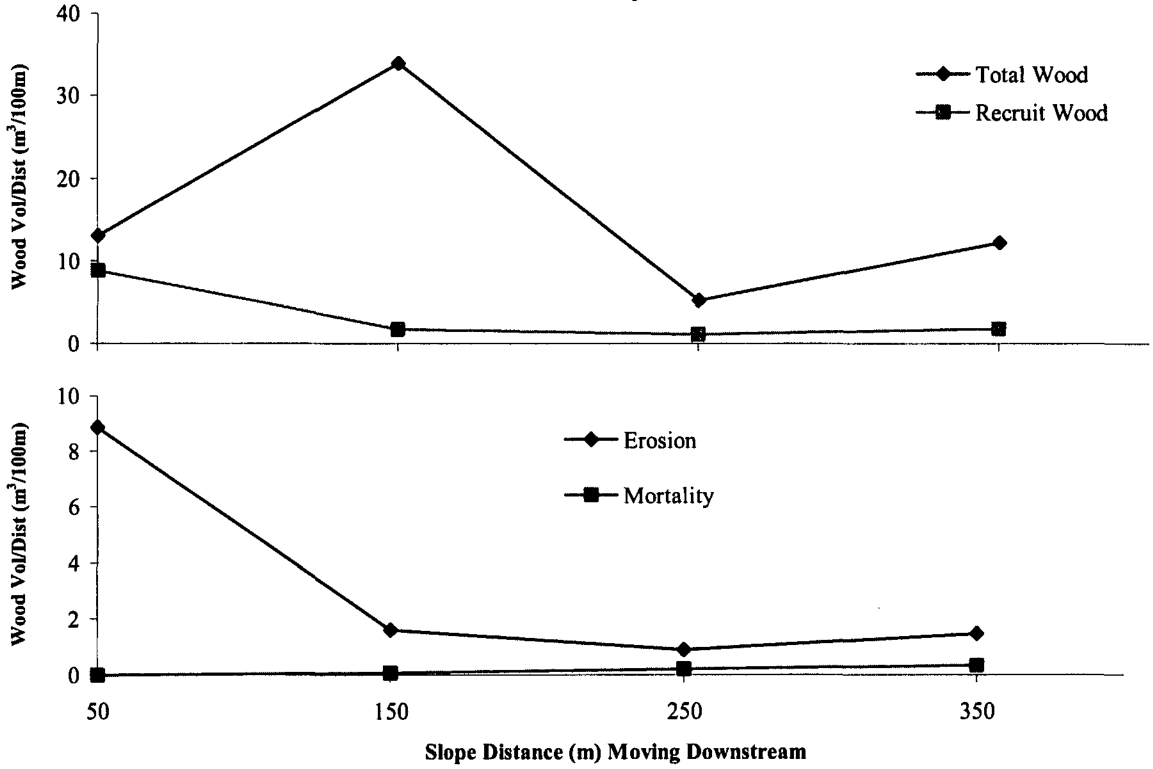
Little North Fork Noyo - Reach #6

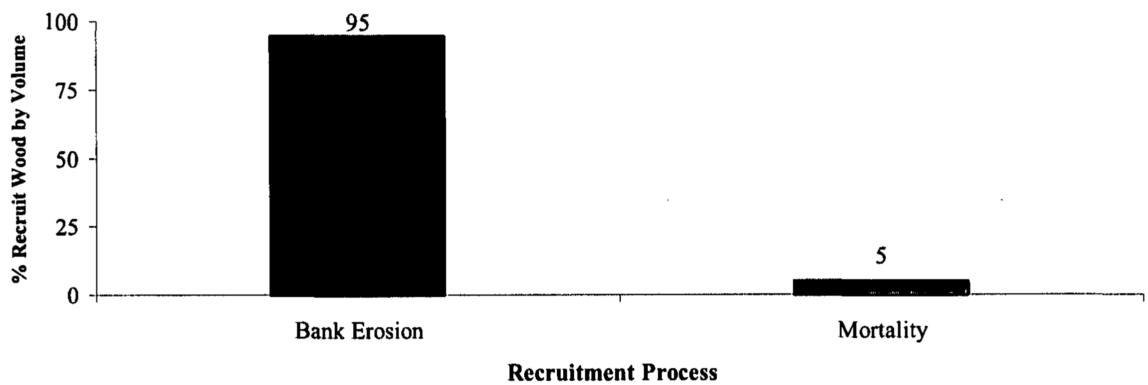


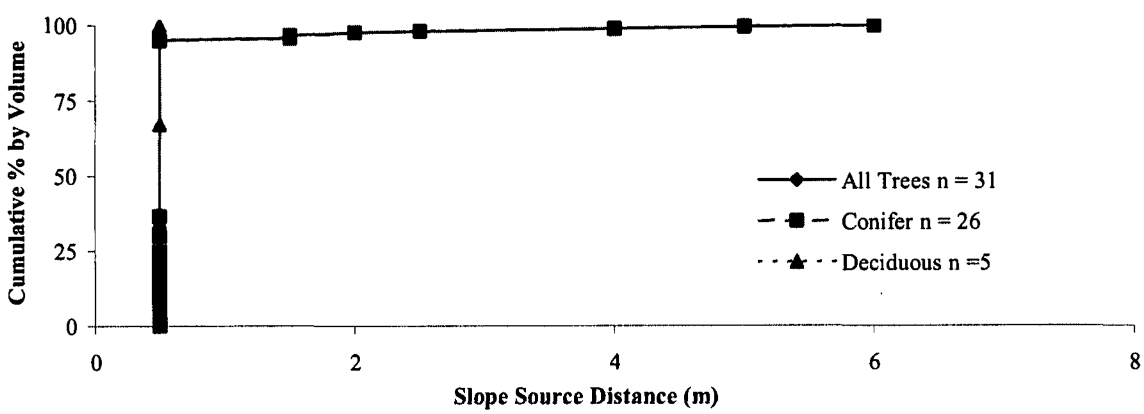




Little North Fork Noyo - Reach #7







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