Dynamics of wood in stream networks of the western Cascades Range, Oregon

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Abstract: We develop and test a conceptual model of wood dynamics in stream networks that considers legacies of forest management practices, floods, and debris flows. We combine an observational study of wood in 25 km of 2nd- through 5th-order streams in a steep, forested watershed of the western Cascade Range of Oregon with whole-network studies of forest cutting, roads, and geomorphic processes over the preceding 50 years. Statistical and simple mass balance analyses show that natural process and forest management effects on wood input, transport processes, and decomposition account for observed patterns of wood in the stream network. Forest practices reduced wood amounts throughout the network; in headwater streams these effects are fixed in stream segments bordered by cuts and roads, but in larger channels they are diffused along the channel by fluvial transport of wood. Landforms and roads limited delivery of wood by debris flows to mainstem channels. Network dynamics studies and watershed management plans should include spatial patterns of debris flow initiation and runout, flood redistribution, and reduction of wood in the network by forest cutting and intentional wood removal from channels on time scales of forest succession and recurrence of major floods.

Résumé : Nous avons développé et testé un modèle conceptuel de la dynamique des bois dans des réseaux de cours d'eau qui tient compte de l'héritage des pratiques d'aménagement forestier, des inondations et du mouvement des débris. Nous combinons une étude basée sur l'observation des bois sur 25 km de cours d'eau de 2^{e} au 5^{e} ordre dans un bassin versant boisé et aux pentes abruptes situé dans la partie ouest des Cascades, en Oregon, à des études de réseau des coupes forestières, des chemins et des processus géomorphologiques au cours des 50 dernières années. Des analyses statistiques et de bilans simples de masse montrent que les effets des processus naturels et de l'aménagement forestier sur l'apport, les processus de transport et la décomposition des bois expliquent les profils observés de présence des bois dans le réseau de cours d'eau. Les pratiques forestières ont réduit les quantités de bois partout dans le réseau; dans les cours d'eau situés en amont, ces effets sont limités aux segments de cours d'eau bordés par des coupes et des chemins mais, dans les cours d'eau plus larges, ils sont répartis le long du cours d'eau par le transport fluvial des bois. Le relief et les chemins ont limité l'apport de bois en limitant le mouvement des bois vers l'axe fluvial. Les études de dynamique de réseau et les plans d'aménagement de bassin versant devraient inclure le profil spatial du mouvement des débris, de son déclenchement jusqu'à ce qu'il cesse, de la redistribution causée par les inondations, de la diminution des bois dans le réseau à cause de la coupe forestière et de l'enlèvement intentionnel des bois dans les cours d'eau, et cela à l'échelle de temps de la succession forestière et de la récurrence des inondations majeures.

[Traduit par la Rédaction]

Introduction

Since the mid-1970s a very large amount of literature has addressed the abundance, spatial patterns, and functions of wood in streams (Gregory et al. 2003), but a general conceptual model of landscape-scale dynamics of wood in stream networks is still emerging. Conceptual models of wood in streams predict declining wood downstream, as wider channels recruit less wood and can transport larger pieces (Lienkaemper and Swanson 1987; Bilby and Ward 1989; Marcus et al. 2002). Many natural processes and forest management practices — clear-cutting and plantation forestry, roads, floods, geomorphic processes, and other mechanisms — also influence wood dynamics in streams (Keller and Swanson 1979; Reeves et al. 1995; Johnson et al. 2000; Benda et al. 2002). Wood dynamics in streams have been described using wood budgets and routing analyses (Lancaster and Hayes 2001; Benda et al. 2002; Meleason et al. 2003).

A general conceptual model of wood dynamics in stream networks could integrate these diverse threads and guide forest and watershed managers. Forest regulations increasingly challenge forest managers to predict wood in streams over large landscapes. The Aquatic Conservation Strategy of the Northwest Forest Plan (USDA Forest Service and USDI Bureau of Land Management 1994), for example, requires forest management plans to consider the cumulative upstream effects of harvest and roads as well as past effects of

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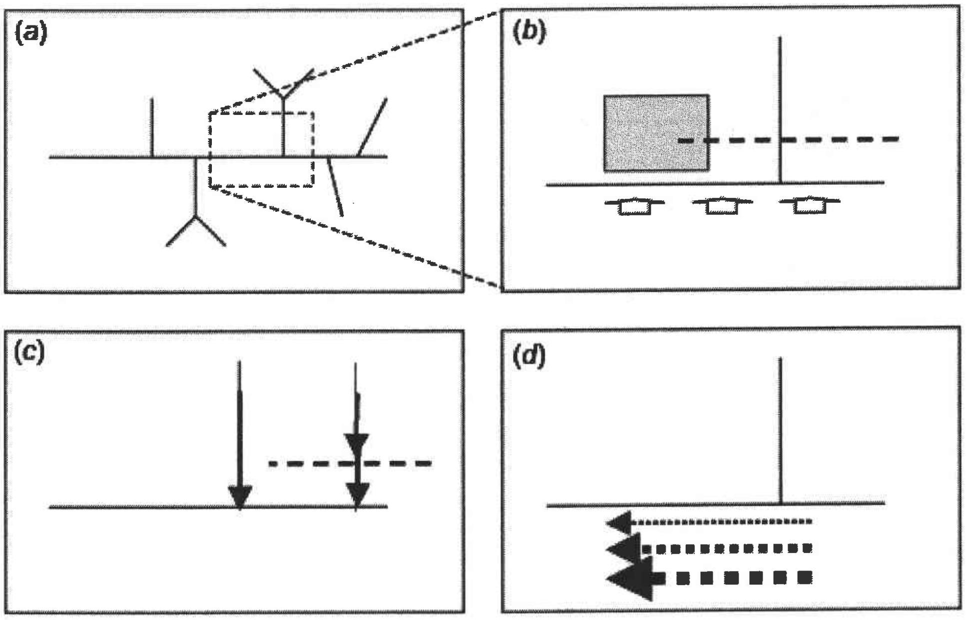
Fig. 1. Conceptual model of wood source and transport processes in a stream network. (*a*) a stream network (solid thin black lines) consists of a set of locations at which tributaries join higher-order (3rd- to 5th-order) streams, referred to as "mainstem" streams in this paper; (*b*) wood delivery to streams along channel margins (open arrows) may be reduced by forest harvest (shaded box) and roads (thick broken line); (*c*) debris flows (black arrows) from tributary streams may convey wood to the mainstem if the debris flow reaches the mainstem; (*d*) fluvial redistribution of wood may occur at low, intermediate, and high rates, depending on channel width.



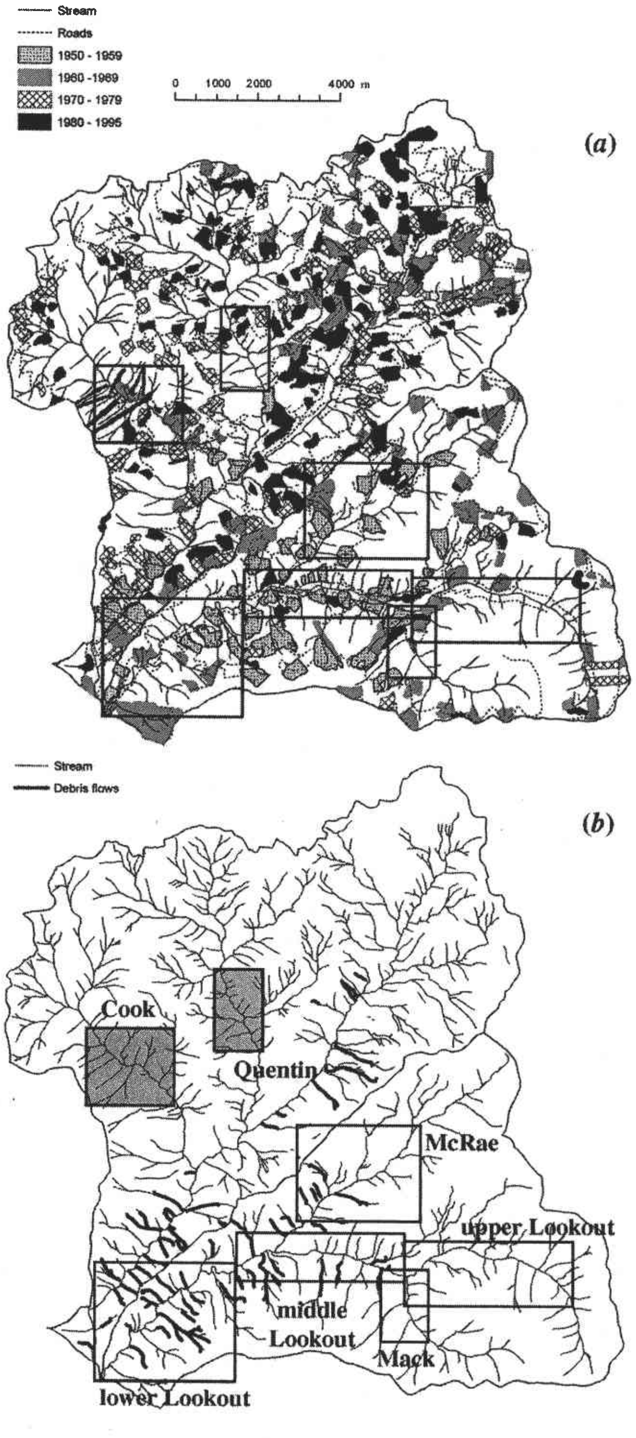
floods and landslides on wood in streams. Equally challenging for forest managers are questions about the effects of road decommissioning or forest management in riparian buffer zones on wood patterns in large stream networks.

Conceptual and technical advances in geospatial analysis, landscape ecology, and long-term ecosystem science provide the basis for a major advance in landscape perspectives on wood in streams. Landscape concepts, including interactions between patchworks and networks, legacies, and network dynamics, are relevant to wood in streams. Forest landscapes consist of patchworks of forest stands of different ages established after disturbance events, including young forests created by past forest cutting (Franklin and Forman 1987; Ripple et al. 1991), networks of roads built to access harvest units (Jones et al. 2000; Forman et al. 2003), and the stream network. Stream network morphology — a population of channels and their confluences — helps predict the spatial distribution of physical diversity in stream networks (Benda et al. 2004*a*). During natural disturbances such as floods and debris flows, forest patchworks and road and stream networks interact, affecting movement of water, sediment, and wood (Swanson et al. 1998; Wemple et al. 2001). Biological legacies — biotic structures that persist from a predisturbance ecological system — shape ecological and physical processes after natural and human disturbances (Dale et al. 2005). Despite their relevance to wood in streams, no general conceptual model unites these concepts and techniques to describe the dynamics of wood in managed and unmanaged forest stream networks.

Building on concepts in Swanson (2003), we develop a network dynamics conceptual framework to explain patterns of wood in stream networks. The conceptual framework (Fig. 1) considers how different combinations of wood inputs from adjacent forest, debris flows, and fluvial redistribution are arranged in a landscape, producing variations in wood in the stream network (Fig. 1*a*). The framework includes wood contributions from streamside forests to streams (Fig. 1*b*) by tree fragmentation, windthrow, bank erosion, and other processes (Keller and Swanson 1979; Lienkaemper and Swanson 1987; McDade et al. 1990; Johnson et al. 2000; Meleason et al. 2003). It also includes effects of forest harvest, roads, and natural processes, such as wildfire and windthrow, on delivery of wood to streams (Benda and Sias 1998; Zelt and Wohl 2004). Clear-cutting removes wood from streamside areas and may have involved salvage logging of downed trees from stream channels. Where mature (80–200 years old) and old-growth (>200 years old) forests are replaced, forest plantations provide much smaller wood pieces to streams. Roads directly replace trees in streamside forests, may involve logging of "hazard trees" in stands adjacent to streams, and provide access for salvage logging from streams.

The conceptual model also includes effects of debris flows on wood in stream networks (Fig. 1*c*). Debris flows are rapid movements of from hundreds to thousands of cubic metres of sediment, soil, and organic matter, including large wood, down steep, narrow headwater channels (Swanson and Dyrness 1975; Benda et al. 2002; May and Gresswell 2003; Reeves et al. 2003); they are common in steep, forested landscapes of the Pacific Northwest (Sidle et al. 1985; Benda and Cundy 1990; Snyder 2000). Debris flows may move wood from a tributary to a mainstem and redistribute wood within tributaries and the mainstem (May and Gresswell 2004; Bigelow et al. 2007). Clear-cutting, roads, and wildfire influence the initiation and stopping points of debris flows (Swanson and Dyrness 1975; Wemple et al. 2001).

Fig. 2. Study streams in the upper Blue River drainage watershed, western Cascades, Oregon. Locations of seven study streams (boxes) relative to (*a*) clearcuts (young forest plantations) and roads, coded by decade and (*b*) mapped debris flows in 1st order channels of the Lookout Creek watershed and parts of upper Blue River watershed, 1946–present (Dyrness 1967; Swanson and Dyrness 1975; Swanson et al. 1998; Snyder 2000). Cook and Quentin creeks were not included in past debris flow inventories, though evidence of debris flows were recorded during this study.



Thus, debris flow wood inputs interact with the pattern of vegetation patches, roads, valley floor morphology, and fluvial redistribution (Fig. 1*b*, 1*c*, and 1*d*).

The conceptual model also includes fluvial transport of wood (Fig. 1*d*), which occurs when logs are floated or rolled downstream (Braudrick et al. 1997; Gurnell et al. 2002). The fluvial transport capacity of a stream segment is a function of the ratios of wood piece length to channel width and piece diameter to streamflow depth (Lienkaemper and Swanson 1987; Bilby and Ward 1989; Braudrick et al. 1997). In general, fluvial transport of wood increases downstream. Clear-cutting and roads increase peak flows in steep, forested watersheds (Jones and Grant 1996), with possible indirect effects on wood movement.

This study examines the interacting effects of channel width, geomorphic processes, and the legacy of clearcuts and roads on wood inputs and redistribution in streams from 1948, when forestry practices began, to 2002 in a 200 km^2 forested watershed in the western Cascade Range, Oregon. We distill these field observations into a landscape-scale conceptual model that considers spatial interactions among road and stream networks, forested patches, and fluvial geomorphic processes to explain spatial and temporal patterns of wood in the stream network and to contribute to the emerging general framework for understanding the dynamics of wood in stream networks.

Methods

Study area

The study was conducted in 2002 in seven 1.5–5.0 km long sections of 3rd- through 5th-order streams (upper, middle, and lower Lookout, Mack, McRae, Quentin, and Cook creeks) in the Blue River watershed in the central Oregon Cascades (44.2°N, 122.2°W) (Fig. 2, Table 1). The study area consists of deeply dissected mountainous terrain with hillslope gradients ranging from 20% to 80%, formed from volcanic rock with highly varied susceptibility to erosion (Swanson and James 1975). The climate is maritime; most precipitation falls from November to March, and mean monthly temperature ranges from 2.1 °C in December to 17.5 °C in August (Smith 2002). Annual precipitation ranges from 2300 mm in lower elevations, mainly as rain, to over 3550 mm at upper elevations, primarily as snow (Swanson and Jones 2002). Forests in the study area are composed primarily of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don), with bigleaf maple (*Acer macrophyllum* Pursh), red alder (*Alnus rubra* Bong.), and willow (*Salix* spp.) common in riparian areas. Over 75% of the area consists of old-growth or mature forest stands regenerated after widespread fire ("unmanaged forests"), with maximum tree heights >70 m (Morrison and Swanson 1990). The remaining 25% of the study area is composed of forest plantations established after clear-cutting (Fig. 2*a*).

Road construction and forest harvest from 1950 to 1990 created a pattern of dispersed patch clearcuts (20–40 ha) accessible by several hundred kilometres of roads in the study area (Wemple et al. 1996). Most road construction and harvest occurred from 1950 to the early 1970s in Look-

Table 1. Characteristics of sampled streams in Lookout Creek and Blue River watersheds, Oregon.

Section of stream	Order	Sampled length (km)	Range of drainage area (ha)	Channel width (m)	Channel gradient (°)
Lookout					
Upper	2	1.1	405–630	6±2	8.9±1.3
	3	3.9	730–1710	12±3	7.7±2.1
Mack	3	1.50	490–860	15±3	6.3±1.9
McRae	3	2.05	515–830	12±3	4.1±1.7
	4	1.85	1130–1445	19±4	3.1±0.6
Middle	4	3.65	2575–3425	22±8	4.5±1.5
	5	0.75	4985–5275	46±12	2.5±0.8
Lower	5	5.0	5275–6240	27±8	1.7±0.6
Blue River					
Cook	4	3.1	985–1800	18±3	2.3±0.8
Quentin	4	2.1	1625–2215	19±3	2.0±1.2
Total		25.0			

out Creek (including McRae and Mack Creek sample sites) and from 1960 through the 1980s in upper Blue River (Cook and Quentin sites) (Fig. 3; Jones and Grant 1996; Skaugset and Wemple 1999). In-stream salvage logging occurred during the 1960s and early 1970s; this effect can be estimated by proximity of roads and harvests to streams. Two large storm events since 1950 (December 1964 – January 1965 and February 1996) initiated extreme floods and debris flows (Fig. 2*b*) (Swanson et al. 1998; Snyder 2000; Swanson and Jones 2002).

Field methods

A total of 25 km of stream length was surveyed in some 2nd-order and all 3rd-, 4th-, and 5th-order channels in Lookout Creek and selected 3rd and 4th-order channels in upper Blue River (Table 1, Fig. 2). All pieces of wood ≥10 cm diameter and 1 m in length (minimum volume = 0.008 m^3) in the active channel were located and measured. The active channel was defined as the area in which wood movement was affected by a 50 year flood event, using evidence from the 1996 flood that was still obvious in 2002, such as the condition and arrangement of wood pieces (Swanson et al. 1998). Each piece was classified as "single" (isolated) or as part of an "accumulation" (≥3 pieces of in-stream wood with >2 points of contact). Each piece was assigned to a 100 m stream segment based on the location of its centermost point. Wood diameter and length were estimated using a visual classification scheme incorporating three diameter classes (10–30, 30–60, and >60 cm), and four length classes (1–5, 5–10, 10–20, and >20 m). Mean volume for each size and length class combination was calculated using an allometric relationship based on 414 field-measured pieces of wood sampled from several randomly chosen locations in the Lookout Creek watershed (Table 2). Wood volumes of all pieces counted were summed and expressed per 100 m of stream length. Large pieces were defined as exceeding 1.87 m^3 and were 30–60 cm in diameter and >10 m in length or >60 cm in diameter and >5 m in length (Table 2). The width of the active channel was measured using an Impulse laser surveyor at roughly 25 m intervals. Locations (starting and ending points) of adjacent natural and human disturbances (e.g., windthrow, bank erosion, harvest units, and roads) were noted (Czarnomski 2003; Dreher 2004).

Classification of stream segments by wood source and transport process

Each of the stream segments was classified based on the age of adjacent streamside forest and the presence of roads using ArcView version 3.2 geographic information system (GIS) software (Czarnomski 2003). GIS layers of the stream network, watershed boundaries, roads, and forest harvest patches were obtained from Willamette National Forest. The stream layer was dynamically segmented (sensu Longley et al. 2001) into 50 m intervals and rectified to the field data using major landforms, harvest units, and road and stream intersections as reference points.

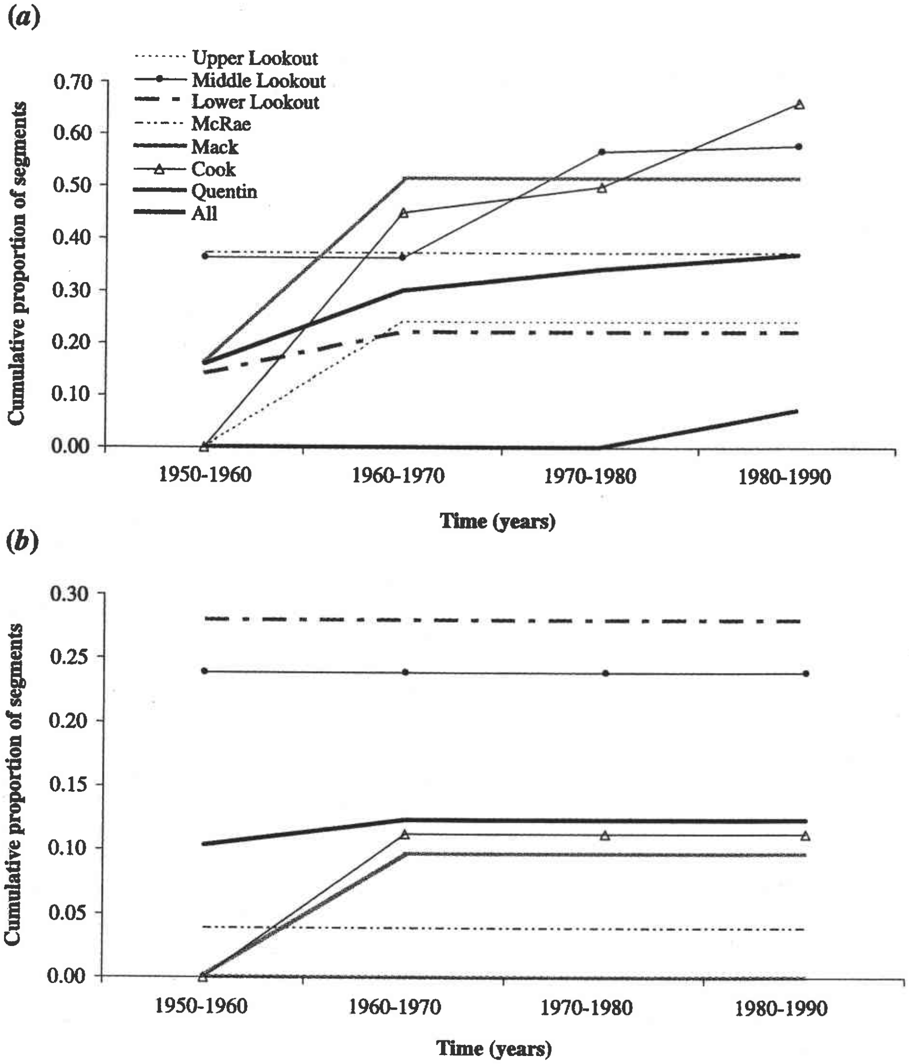
A stream segment was defined as "adjacent" to a harvest or road if ≥50% of its length was within 40 m of the harvest or road. Most wood is contributed by streamside forests from within 40 m of the stream (Harmon et al. 1986; McDade et al. 1990; Swanson et al. 1990; Meleason et al. 2003), but taller than the 60 m height commonly achieved by mature and old-growth Douglas-fir can contribute wood from greater distances. The percent length of each 50 m stream segment adjacent to a harvest unit or road was calculated using GIS software for each of four harvest distances on either side of the stream line: 0 m, 1–10 m, 10–20 m, and 20–40 m. These values were grouped into 0 m, 1–40 m, and >40 m for analysis.

Each stream segment in the Lookout Creek watershed also was classified according to its fluvial transport capacity for wood and whether a debris flow had entered that segment from a tributary in the past 50 years (Dreher 2004). Segments affected by slow-moving earthflows were too few to be included in this analysis. Fluvial transport capacity classes were defined based on stream order, measured channel widths, and drainage areas: low (2nd-order, 4–10 m, 400–800 ha), intermediate (3rd–4th-order, 9–40 m, 500–5000 ha), and high (5th-order, 18–62 m, 5000–6200 ha) fluvial transport capacity. Debris flow pathways were obtained from the H.J. Andrews Forest online spatial database (www.fsl.orst.edu/lter/index.cfm), based on Snyder (2000). A stream segment was classified as affected by debris flow if either (*i*) it was contained in the mapped debris flow runout pathway from 1996 (two instances, mapped in Wondzell and Swanson 1999 and Johnson et al. 2000) or (*ii*) a debris flow entered the channel from a tributary within 300 m upstream of the segment between 1950 and 1995 (six instances, mapped in Swanson et al. 1998 and Snyder 2000) (Fig. 2*b*).

Statistical analyses

Wood volume was autocorrelated at up to 100 m but not beyond 100 m (Czarnomski 2003), so observations were combined into 250 segments 100 m long for analysis. Wood volumes, numbers of large pieces, and numbers of accumulations (dependent variables) were related to fluvial transport capacity, debris flow influence, and adjacency to harvest and (or) roads (independent variables) using analysis of variance (ANOVA, PROC MIXED in SAS version 8.2, SAS Institute Inc., Cary, North Carolina). To meet ANOVA assumptions,

Fig. 3. Intensity of streamside clear-cutting (*a*) and roads (*b*) in the study streams. Cumulative proportion of streamside clearcut within 40 m of the stream, by decade. A value of 0.5 means that 50% of the length of the stream had a clearcut or road on one or both sides; a value of 1.0 would mean that the entire stream length had a clearcut or road on one or both sides.



stream segments with zero pieces of large wood were removed from analyses of large pieces. Dependent variables were natural log-transformed for statistical analysis; group means reported in results have been back-transformed. Independent variables were tested for independence prior to ANOVA using χ^2 analyses (SAS version 8.2 PROC FREQ). Significant between-group differences were determined using post-hoc pairwise comparisons with *p* values adjusted using a Bonferroni procedure (Ramsay and Schafer 1997).

Model of wood in streams over time

The legacies of harvest and flood effects on wood volume in a given stream segment play out over many decades in old-growth forest systems. To explore the temporal dynamics of the four types of wood dynamics in channels (Fig. 1), we simulated wood dynamics over time in streams, contrasting the effects of (*i*) low versus intermediate and high fluvial transport capacity under mature and old-growth forest with (*ii*) the effects of converting streamside forest to young forest. The model predicted the wood volume in a stream segment as

$$V_t = V_{t-1}\, e^{-\mathrm{k}} + I_t - O_t$$

where V_t is the volume of wood in a stream (m^3/ha) in time period t; k is the decay constant, including loss from biological decomposition, physical abrasion, and fragmentation of pieces less than the minimum size; I_t is the wood input to the stream segment from adjacent forest and upstream in time period t; and O_t is the number of losses of wood greater than the minimum size for decay from the stream segment to downstream in time period t. Input rates in old-growth forest were 1.2 m^3/100 m, which is consistent with long-term data from Mack Creek (Meleason et al. 2003). Wood depletion by decomposition and fluvial transport of particulate organic matter to the banks or downstream segments was assumed to be 2% per year, based on measured rates from long-term log decomposition experiments (M.E. Harmon, unpublished data, 9 December 2006) and estimates