

Factors affecting distribution of wood, detritus, and sediment in headwater streams draining managed young-growth red alder - conifer forests in southeast Alaska

Takashi Gomi, Adelaide C. Johnson, Robert L. Deal, Paul E. Hennon, Ewa H. Orlikowska, and Mark S. Wipfli

Abstract: Factors (riparian stand condition, management regimes, and channel properties) affecting distributions of wood, detritus (leaves and branches), and sediment were examined in headwater streams draining young-growth red alder (*Alnus rubra* Bong.) - conifer riparian forests (40 years old) in southeast Alaska. More riparian red alder were found along streams affected by both timber harvesting and mass movement than in streams affected by timber harvesting alone. Young-growth stands produced little large wood material (diameter >10 cm) and had little effect on altering the size distribution of functional large wood in channels, although more alder wood pieces were found in streams with greater numbers of riparian alder trees. Legacy wood pieces (>40 years old) remained in channels and provided sites for sediment and organic matter storage. Despite various alder-conifer mixtures and past harvesting effects, the abundance of large wood, fine wood, and detritus accumulations significantly decreased with increasing channel bank-full width (0.5-3.5 m) along relatively short channel distances (up to 700 m). Changes in wood, detritus, and sediment accumulations together with changes in riparian stand characteristics create spatial and temporal variability of in-channel conditions in headwater systems. A component of alder within young-growth riparian forests may benefit both wood production and biological recovery in disturbed headwater stream channels.

Resume: Les facteurs (etat du peuplement riverain, regimes d'aménagement et propriétés du chenal) qui affectent la distribution du bois, des détritus (feuilles et branches) et des sédiments ont été examinés dans les cours d'eau de tête drainant de jeunes forêts riveraines d'aulne rouge (*Alnus rubra* Bong.) et de conifères, «40 ans» dans le sud-est de l'Alaska. Plus d'aulnes rouges riverains ont été observés le long des ruisseaux affectés par la récolte du bois et les mouvements de masse que près des cours d'eau affectés seulement par la récolte du bois. Les jeunes peuplements produisaient peu de gros débris ligneux (diamètre ~10 cm) et avaient peu d'effet sur la modification de la distribution des dimensions du gros bois fonctionnel dans les chenaux, quoique plus de pièces de bois d'aulne aient été trouvées dans les cours d'eau ayant un plus grand nombre d'aulnes riverains. Les pièces de bois restantes (>40 ans) sont demeurées dans les chenaux et ont constitué des sites de stockage pour les sédiments et la matière organique. En dépit des mélanges variés d'aulne et de conifères et des effets des récoltes antérieures, l'abondance des accumulations de gros bois, de petits bois et de débris diminuait significativement avec l'augmentation de la largeur de pleins bords du chenal (0,5 à 3,5 m) sur des distances relativement courtes de ce dernier (jusqu'à 700 m). Les variations dans les accumulations de bois, de détritus et de sédiments combinées aux variations dans les caractéristiques des peuplements riverains créent une variabilité spatiale et temporelle des conditions dans les cours d'eau de tête. Une certaine proportion d'aulne dans les jeunes forêts riveraines peut être bénéfique pour la production de bois et la restauration biologique dans les chenaux perturbés des cours d'eau de tête.

[Traduit par la Rédaction]

Received 6 December 2004. Resubmitted 7 August 2005. Accepted 8 November 2005. Published on the NRC Research Press Web site at <http://cjfr.nrc.ca> on 22 March 2006.

T. Gomi.¹ Japan Science and Technology Agency, Geo-Hazards Division, Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan.

A.C. Johnson, P.E. Hennon, and E.H. Orlikowska. USDA Forest Service, Pacific Northwest Research Station, 2770 Sherwood Lane, Suite 2A, Juneau, Alaska, 99801, USA.

R.L. Deal. USDA Forest Service, Pacific Northwest Research Station, 620 SW Main Street, Suite 400, Portland, Oregon 97205, USA.

M.S. Wipfli. USGS Alaska Cooperative Fish and Wildlife Research Unit, Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska, 99775, USA.

¹Corresponding author (e-mail: gomi@slope.dpri.kyoto-u.ac.jp).

Table 1. Characteristics of streams and riparian zones of the study sites.

	No. of 25 m reaches	Mean channel gradient (%)	Mean bank-full width (m)	Total BA (live and dead) (m ² ·ha ⁻¹)	BA of riparian red alder (%)	BA of dead trees (m ² ·ha ⁻¹)
Upland reach						
Big Spruce	4	16.3	0.89	77.7	31.5	7.6
Broken Bridge East	7	10.7	2.24	53.4	47.3	3.9
Broken Bridge West	7	22.5	1.47	57.3	38.7	2.6
Brushy	3	15.5	1.11	62.3	53.3	3.2
Cotton	5	27.2	3.40	70.5	43.2	1.6
Gomi	6	26.1	1.04	52.5	25.0	0.5
Mile 22	5	18.3	1.19	53.8	29.2	1.8
Cedar 1	7	19.3	1.60	56.4	35.6	1.9
Cedar 2	5	18.8	1.97	65.6	3.8	1.5
Creature	7	18.9	1.06	47.9	9.9	0.2
Good Example	6	13.6	0.93	48.5	1.5	1.1
Lost Bob	7	19.5	0.68	41.0	0.0	0.1
Morning	6	14.5	1.07	52.5	3.9	1.3
Lowland reach						
Broken Bridge East	7	≈4.0	2.45	68.5	49.3	2.4
Cotton	7	7.9	4.30	61.6	14.1	0.8
Creature	7	≈5.0	1.06	42.0	49.8	3.5
Cedar 1	4	3.6	1.60	60.9	15.7	3.3
Cedar 2	7	2.7	3.22	52.5	66.8	8.9
Good Example	7	2.3	1.36	59.3	11.3	2.4

Note: Disturbance owing to logging activities includes yarding and landing. Disturbances owing to mass movement include landslides and debris flows. (Swanston and Marion 1991; Johnson et al. 2000; Gomi et al. 2004). Channel gradients in the lower reaches of Broken Bridge and Creature were stand structures and compositions. BA, basal area.

Introduction

Various geomorphic, hydrologic, and biological factors of channels and riparian zones affect distributions and accumulations of wood, detritus (leaves and branches), and sediment in headwater streams. Mass movements alter re-distributions and accumulations of wood pieces from headwaters to downstream reaches (Johnson et al. 2000; May and Gresswell 2003; Gomi et al. 2004). Channel width relative to the length of wood relates to transport capacity of wood pieces: thus, channel width controls distributions and accumulations of wood (Keller and Swanson 1979; Vannote et al. 1980; Bilby and Ward 1989; Jackson and Sturm 2002). Timber harvesting and riparian management practices modify recruitment of both large and fine wood pieces (Andrus et al. 1988; Ralph et al. 1994; Gomi et al. 2001). Stand density and species composition of riparian stands modify the types, sizes, and amounts of wood pieces in channels (Hedman et al. 1996; Rot et al. 2000; Benda et al. 2002).

A wider range of red alder (*Alnus rubra* Bong.) and conifer mixtures is often observed in headwater riparian zones in the managed young-growth forest of the Pacific Northwest (Alaback and Sidle 1986; Harrington et al. 1994). Corridors of pure red alder or mixed red alder - conifer stands establish naturally in riparian zones where physical disturbances (floods and mass movements) have exposed or deposited mineral soil (Gregory et al. 1991; Johnson and Edwards 2002; Wipfli et al. 2003). Heavy soil disturbance from tractor logging, high-lead cable operations, and construction of roads and landings also creates favorable conditions for re-

generating red alder in young-growth forests (Harrington et al. 1994; Deal et al. 2004).

Stand age and tree species composition of riparian forests potentially affect distributions and accumulations of wood and organic matter in channels. Red alder has rapid juvenile growth (Harrington et al. 1994) and higher initial tree density and mortality than conifer stands (Minore and Weatherly 1994; Hibbs and Giordano 1996). Therefore, riparian red alder stands initially provide more wood pieces than riparian conifer stands because of this rapid juvenile growth and dead wood production (Grette 1985; Andrus et al. 1988; Beechie et al. 2000). However, alder wood pieces are small (Grette 1985) and decompose and fragment quickly (Harmon et al. 1986; Cederholm et al. 1997; Bilby et al. 1999). As a result, persistence and in-stream functions of alder wood pieces may differ from those of conifers. Wood pieces functioning for sediment storage in channels potentially vary depending on the mixture of alder-conifer in the riparian stands (Gomi et al. 2001; May and Gresswell 2003). Because alder riparian stands produce more leaves and branches, accumulation of detritus (leaves and branches) may also differ in streams with different riparian stand composition (Vannote et al. 1980; Bilby 1981; Sidle 1984; Gregory et al. 1991; Volk et al. 2003). Riparian stand conditions, in-channel topographic properties, and the history of management and disturbance need to be considered to understand the factors controlling the distribution and accumulation of wood, detritus, and sediment in headwater streams (Gomi et al. 2002; Moore and Richardson 2003; Richardson et al. 2005).

The objectives of this study were to (i) contrast the amount and spatial distribution of wood pieces in channels over a

Mean DBH (cm) of stand (≥ 10 cm)				Mean DBH (cm) of stand (3–10 cm)				Types and year of soil disturbance
Live conifer	Live red alder	Dead conifer	Dead red alder	Live conifer	Live red alder	Dead conifer	Dead red alder	
20.6	24.3	15.9	13.2	6.8	8.3	5.8	5.2	Logging and mass movement (1961)
23.3	20.0	—	13.5	5.6	7.1	3.7	5.8	Logging and mass movement (1961)
21.2	19.7	—	10.2	5.7	8.3	4.6	5.4	Logging and mass movement (1961)
27.5	22.2	—	10.7	6.3	—	4.3	6.5	Logging and mass movement (1961)
20.7	25.6	—	14.5	6.0	7.0	5.0	5.5	Logging and mass movement (1961, 1979)
20.7	21.1	—	—	5.7	8.7	4.0	5.2	Logging and mass movement (1961)
22.1	25.3	21.2	11.7	6.6	—	4.0	5.9	Logging and mass movement (1961)
17.8	18.6	10.3	10.9	6.1	8.9	4.9	6.0	Logging
19.6	22.5	—	—	6.0	6.3	5.5	—	Logging
21.1	16.5	—	—	5.7	6.6	5.7	4.2	Logging
16.1	22.5	12.7	—	5.8	7.5	4.1	—	Logging
17.4	—	—	—	5.8	—	4.1	—	Logging
19.4	13.1	—	—	6.5	6.5	4.6	3.4	Logging
27.8	22.3	—	12.3	5.7	—	6.7	7.2	Logging and mass movement (1961)
23.9	25.6	12.3	17.1	5.5	3.4	4.4	7.3	Logging and mass movement (1961, 1979)
23.6	15.4	19.8	12.8	5.9	6.7	6.4	5.1	Logging and mass movement (1961)
17.0	18.9	—	—	6.2	6.0	4.6	4.6	Logging
18.7	16.4	12.0	—	5.4	7.0	3.5	5.2	Logging
19.9	14.4	16.2	—	6.4	7.2	5.1	6.8	Logging

Types and year (in parentheses) of soil disturbances were estimated using aerial photographs, landslide inventory (Helmers 1961–1985), and field observations estimated using GIS topography maps. Numerical variables are expressed as means. Also see Orlikowska et al. (2004) for detailed descriptions of riparian

wide range of riparian alder-conifer mixtures in headwater streams with young-growth riparian forest, (ii) evaluate the distribution and accumulation of sediment and detritus that may relate to composition of alder and conifer mixture, and (iii) identify factors affecting distribution of wood, detritus, and sediment along headwater channels. Finally, we construct a conceptual model for factors associated with riparian stand dynamics and physical condition of streams along headwater systems of managed young-growth forests.

Study sites

This study was conducted in the Maybeso Experimental Forest and adjacent Harris River watershed in the Tongass National Forest on Prince of Wales Island in southeast Alaska (Fig. 1). Climate in this area is maritime, cool and moist, with a mean temperature of 10 DC (minimum -10 DC, maximum 25 DC). Mean annual precipitation ranges from 2500 to 3000 mm of which approximately 70% falls between October and April as a result of Pacific frontal systems (Meehan et al. 1969). These basins are U-shaped deglaciated valleys composed primarily of greywacke with interbedded basalt flows and pyroclastic rocks and include conglomerate, sedimentary breccia, chert, shale, and sandstone (Eberlein et al. 1983). Bedrock is covered by a varying thickness of glacial till formed during the late Wisconsin glacial advance. Soil depth plus the thin veneer of glacial till ranges from 0.30 to 1.0 m. Forest vegetation is dominated by western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and western redcedar (*Thuja plicata* Donn ex D. Don). Red alder is common

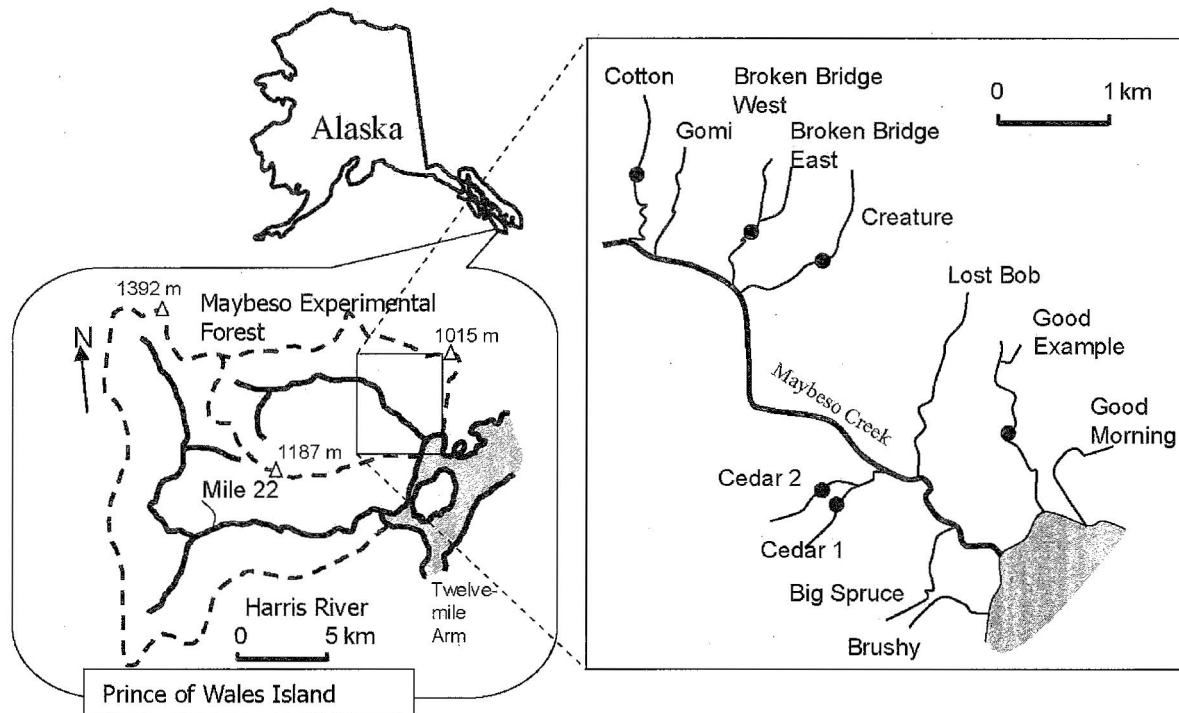
where soils have been disturbed by mass movements and timber harvesting. Commercial timber harvesting occurred from 1953 until 1957 in the Maybeso Valley and from 1959 to 1961 in the Harris River basin (Meehan et al. 1969). No resident fish were found in the upper reaches (channel gradient generally >10%) of the headwater streams, whereas both resident trout and juvenile salmonids were found in the lower reaches (channel gradient typically <10%) (Bryant et al. 2004).

Thirteen perennial study streams within young-growth riparian forests were selected to provide a range of alder-conifer mixtures based on total basal area (Table 1). All streams were affected by timber harvesting in the 1950s and 1960s. Ten of these streams originated from midslope positions, whereas three streams (Cotton, East Broken Bridge, and Mile 22) originated in alpine areas. Mass movements affected eight of our study streams in 1961 and 1979 (Table 1) (Swanston and Marion 1991; Johnson and Edwards 2002). In these channels, sediment and wood, transported as channelized debris flows, deposited in lower reaches and did not reach the main channel of Maybeso Creek, which is typical of deglaciated, U-shaped valleys (Fig. 2) (Swanston and Marion 1991; Johnson et al. 2000; Gomi et al. 2001). Dominant reach types of upstream channels were step-pool, cascade, and bedrock, whereas pool-riffle and step-pool reaches were dominant in downstream channels (Gomi et al. 2003). Incision of the headwater valley varied from 1 to 10 m.

Methods

Channel reaches 125–325 m long in 13 headwater streams were chosen to assess relationships among the amount of red

Fig. 1. Study site locations. Twelve study streams were located in the Maybeso Experimental Forest, while one study stream (Mile 22) was in the Harris River basin. Broken lines on the map indicate boundaries between upland and lowland reaches of the stream survey.



alder in riparian zones, stream gradient, bank-full width, and wetted width. The wetted and bank-full widths of streams were estimated every 5 m. Bank-full width was defined by the presence of moss and rooted vegetation along the channel margins and the top of banks. Channel gradient was measured using a clinometer. Evidence of mass movement and timber harvesting activities (including location of landings associated with cable yarding operations) around stream channels was documented using aerial photographs taken in 1958, 1962, 1980, 1991, and 1994 and with a mass-movement inventory (A.E. Helmers, USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, Juneau, Alaska, unpublished).

The influence of mass movement on the distribution and accumulation of wood pieces was investigated in two reach types, upland (slopes >10%) and lowland (slopes <10%), in five streams (Fig. 2) (Johnson and Edwards 2002; Orlikowska et al. 2004). Upland reaches were located in steep side slopes of U-shaped valleys, whereas lowland reaches included transitions from side slopes to alluvial fans and floodplains within U-shaped valleys (Gomi et al. 2004). Upland reaches were typically scour and runout zones of mass movement, while lowland reaches were deposition zones (Fig. 2). Wood, detritus, and sediment accumulation were quantified in both upper and lowland reaches.

Tree species composition, stand basal area, stand density, tree size distribution, and number of dead trees were measured in the riparian plots along the 13 study streams (including upper and lower reaches). Live and dead trees in the riparian plots were classified into two categories: 0.1 m diameter at breast height (DBH (1.3 m) and 0.03–0.1 m DBH. Alongside each stream, seven pairs of 5 m x 15 m plots (one

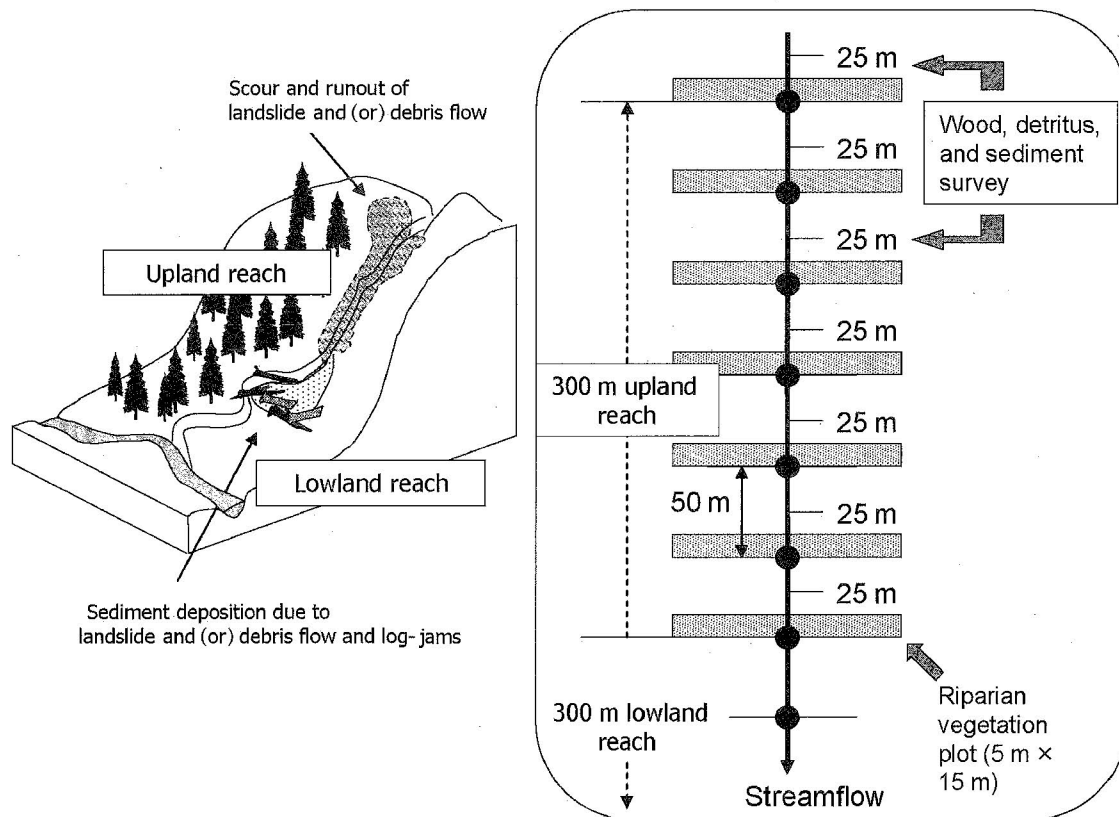
pair on both left and right banks) spaced evenly at 50 m intervals along a headwater channel were established within a 300 m stream reach (Fig. 2). Detailed description of riparian vegetation sampling is given in Orlikowska et al. (2004).

Size and number of wood pieces, accumulation of detritus (leaves and branches), and volume of sediment stored behind wood pieces and other channel obstructions were measured in 25 m stream subreaches within successive 50 m channel reaches along headwater channels (Fig. 2). Woody debris was classified into one of two categories: (i) large wood (LW), pieces >0.5 m in length and >0.1 m in diameter, or (ii) fine wood (FW), pieces >0.5 m in length and 0.03–0.1 m in diameter. In-channel, bank-full, and total lengths, diameter, and position were measured for LW. In-channel length was measured for the entire length of LW pieces located within the wetted channel width. Bank-full length of LW was defined as either a portion or the entire length of LW pieces within bank-full width. Total length of LW included the terrestrial portions (Ralph et al. 1994; Beechie and Sibley 1997). Diameter at the middle of each wood piece was also recorded. Volume (m^3) of a LW piece (V) was estimated for the in-channel, bank-full, and total volume components by

$$[1] \quad V = \pi(D/2)^2L$$

where D and L are the mid-log diameters and appropriate lengths, respectively (Gomi et al. 2001). All LW pieces were classified as functional (interacting directly with streams as base now), transitional (not directly interacting with streams but suspended just above streams and decomposed enough to interact with streams in the near future), and nonfunctional (no interaction with streams and (or) suspended above bank-

Fig. 2. The left side is a schematic view of headwater streams (modified from Gomi et al. 2001). The right side is a schematic illustration of the location of in-channel and riparian zone inventories along streams.



full channels). LW pieces were divided into three types based on species and the period of recruitment: (i) young-growth red alder, (ii) legacy, and (iii) young-growth conifer. These groups were based on field inspection of texture, bark, cut edges, and decay in woody debris. Legacy wood entered from old-growth stands before and during logging in the 1950s. Thus, LW pieces that grew before the logging and were left during logging were also considered legacy pieces. Legacy LW was determined from decay conditions (Harmon et al. 1986; Wallace et al. 2001) and cut edge of pieces. If pieces of conifer wood were recruited after timber harvesting, they were classified as young-growth conifer LW. We could only detect recently recruited alder wood (<10 years old) because alder wood quickly decomposes and fragments (Harmon et al. 1986; Cederholm et al. 1997). FW pieces were surveyed for channel position and number of pieces. Volume of fine organic matter accumulation (detritus), such as accumulations of leaves, small branches, and fine logging slash, was estimated as small (<0.01 m³), medium (0.01–0.1 m³), and large (>0.1 m³). We considered accumulations of leaves and small branches as detritus accumulations because leaves and small branches are the major portion of accumulated detritus within channels (Casas 1997).

Sediment storage volumes (V_{sed}) behind wood and the other in-channel obstructions (e.g., boulders and bedrock) were estimated by taking measurements of width (W_{sed}), length (L_{sed}), and average depth (D_{sed}) of the sediment wedge (Gomi et al. 2001):

$$[2] \quad V_{sed} = 1/3(W_{sed} L_{sed} D_{sed})$$

The approximation of a pyramid-shaped wedge appeared to be appropriate, since the upstream end of stored sediment typically converges to a point in these small channels. Average depth of the sediment wedge was measured using a sediment probe (metal pin) at three points. We pounded the sediment probe into the streambed until hitting bedrock (hard and solid layer) and assumed that measured depth of the sediment wedge was suitable for estimating volume. Cause of sediment deposition was categorized by the formation elements of the debris dam: LW, FW, detritus accumulation, boulders, or bedrock (pocket or bench of bedrock).

Correlations among variables such as physical characteristics of streams (channel gradient and bank-full width), number and volume of LW pieces, number of FW pieces, and volume of stored sediment were calculated in each stream. Correlation analysis was performed separately for data from upper and lower stream reaches. All variables for performing correlation analysis were $\log_{10}(x+1)$ transformed. Because the distributions of diameter and length classes were highly skewed, the Kruskal-Wallis rank sum test was used to compare the size of woody debris among alder, legacy, and conifer pieces. Throughout this study, statistical significance was considered at an alpha of 0.05. All statistical analyses were performed using S-Plus (Venables and Ripley 1997).

Selected study channel sites, consisting of perennial streams having a range of alder-conifer mixtures, were not random

Table 2. Characteristics of wood, detritus, and sediment accumulations.

	BA of riparian red alder (%)	Volume of large wood (m ³ ·m ⁻² ×10 ⁻²)			No. of wood pieces (m ⁻²)		No. of detritus accumulations (m ⁻²)
		In-channel	Bank-full	Outside	Large wood	Fine wood	
Upland reach							
Big Spruce	31.5	3.0	9.8	19.0	0.52	1.27	0.71
Broken Bridge East	47.3	0.2	1.3	2.4	0.13	0.16	0.06
Broken Bridge West	38.7	0.4	1.9	1.7	0.16	0.21	0.27
Shrubby	53.3	4.1	14.5	5.1	0.48	1.33	0.57
Cotton	43.2	4.4	9.5	2.3	0.40	0.34	0.02
Gomi	25.0	4.2	1.3	1.8	0.69	1.25	0.22
22 Mile	29.2	4.4	3.7	12.8	0.61	2.62	0.60
Cedar 1	35.6	1.2	12.6	6.1	0.80	1.02	0.15
Cedar 2	3.8	0.7	15.8	0.0	0.57	1.37	0.18
Creature	9.9	2.2	2.8	10.8	0.25	0.42	0.08
Good Example	1.5	2.7	3.0	8.0	0.66	1.99	0.42
Lost Bob	0.0	3.0	7.4	9.8	0.99	2.05	0.50
Good Morning	3.9	1.0	9.2	8.7	0.67	1.13	0.67
Lowland reach							
Broken Bridge East	49.3	1.8	1.0	1.2	0.19	0.17	0.09
Cotton	14.1	1.1	3.1	1.8	0.34	0.35	0.02
Creature	49.8	4.3	1.5	1.9	0.48	0.74	0.08
Cedar 1	15.7	4.4	6.7	9.9	0.41	1.31	0.20
Cedar 2	66.8	0.6	1.9	1.6	0.12	0.47	0.04
Good Example	11.3	2.4	1.6	2.3	0.45	1.13	0.18

Note: Wood pieces classified as large wood, which were pieces >0.5 m in length and 0.1 m in diameter, and fine wood, which were pieces >0.5 m in branches) were estimated as small ($<0.01 \text{ m}^3$), medium ($0.01\text{--}0.1 \text{ m}^3$), and large ($>0.1 \text{ m}^3$). Volumes of large wood pieces were estimated for the following channel width; bank-full, volume of large wood located within the bank-full width (absence of vegetation); outside, volume of the terrestrial portion of wood pieces and the other in-channel obstructions were classified in the following way: large wood, large wood formed sediment storage; fine wood, fine by boulders and bedrock formed sediment storage. Legacy wood were wood pieces of old-growth forest that were recruited during and at the time of logging

owing to the limited number of streams in the experimental watershed. We assume that ranges of alder-conifer mixtures of riparian stands in our study represented most of the streams in managed young-growth forests of southeast Alaska. To further support our approach and inferences, we note that the landscape from which the streams were selected has basically the same lithology, soils, climate, hydrological processes, natural vegetation, and geomorphic processes (i.e., glaciation and deposition of till). This should minimize any confounding effect of the selection bias.

Results

Characteristics of streams and riparian stands

Upland reaches (125–325 m long) had bank-full widths ranging from 0.7 to 4.3 m and mean stream gradients of 10.7% – 27.2% (Table 1). Lowland channel reaches (175–325 m long) had mean bank-full widths of 1.1 – 4.3 m and mean stream gradients of 2.3% – 7.9% .

Among our upland sites, mean percentage of red alder stand basal area was relatively greater in streams impacted by mass movement compared with those without mass movement (Table 1). More red alder was generally found in lowland reaches (mean = 34.5%) compared with upland reaches (mean = 24.8%) (Table 1). Total riparian stand basal area of both red alder and conifers ranged from 41 to $78 \text{ m}^2 \cdot \text{ha}^{-1}$ and composition ranged from 0% to 67% alder (Table 2).

The amount of red alder was positively correlated with bank-full width ($r = 0.46$, $p = 0.05$).

Mean tree DBH of live riparian conifers (>10 cm DBH) ranged from 16.0 to 27.8 cm, while mean tree DBH of live alders (>0 cm DBH) varied from 14.0 to 25.0 cm (Table 1). Relatively large DBH of live conifer trees were found in streams having greater percentages of alder composition. The basal area of dead snags ranged from 0.1 to $8.9 \text{ m}^2 \cdot \text{ha}^{-1}$. Mean diameters of dead alders (>10 cm DBH) ranged from 10.2 to 17.8 cm; those of dead conifer trees varied from 10.3 to 21.2 cm (Table 1). DBH of small live and dead conifer stands ($3\text{--}10$ cm DBH) ranged from 3.5 to 6.8 cm, whereas DBH of small live and dead alder trees ranged from 3.4 to 8.7 cm.

Wood and detritus

Approximately 6% (ranging from 0% to 42%) of total LW pieces (including in-channel and terrestrial portions) were young-growth red alder trees (Table 2). An average of 42% (ranging from 30% to 54%) of the LW was legacy wood pieces. Forty-five percent of the LW pieces were young-growth conifer and 7% were unknown pieces recruited during or after timber harvesting.

Diameter and length distributions of red alder, conifer, and legacy LW were significantly different based on the Kruskal-Wallis rank sum test (Fig. 3). Median diameter of legacy LW pieces (42 cm) was greater than that of the alder

Types of large wood (%)		Volume of sediment storage ($\text{m}^3 \cdot \text{m}^{-2} \times 10^{-2}$)			
Red alder	Legacy	Large wood	Fine wood	Others	Total
17.4	28.3	0.20	0.56	0.10	0.85
12	28	0.32	0.51	0.88	1.71
14.3	31	0.24	0.36	1.88	2.48
17.5	30	0.47	0.17	1.09	1.73
0	26.6	7.11	0.00	0.55	7.66
NA	6.5	4.29	0.33	0.93	5.55
6.9	37.5	0.71	0.54	0.40	1.65
0	16.7	1.75	0.16	0.47	2.38
2.4	22.7	0.67	0.20	0.54	1.40
1	37.4	0.27	0.07	0.11	0.45
0	21.7	0.76	0.60	0.23	1.59
0	26.7	0.01	0.05	0.06	0.12
0	27.1	0.20	0.07	6.39	6.65
14.8	21	0.71	0.24	0.97	1.93
41.8	7.5	1.90	0.04	5.16	7.10
3.4	22.7	0.63	0.39	3.17	4.19
0	15.4	1.15	0.37	0.08	1.60
0	23.1	0.36	0.27	0.01	0.65
0	24.5	0.70	0.29	0.69	1.68

length and 0.03–0.1 m in diameter. Accumulations of detritus (leaves and three portions: in-channel, volume of large wood located within the wetted large wood located outside the bank-full width. Volumes of sediment stored wood and (or) detritus accumulations formed sediment storage; others, in the 1950s.

LW (12 cm) and conifer LW (18 cm) (Fig. 3). The diameter of legacy wood pieces appeared to be larger than the DBH of existing riparian trees, whereas the diameter of other wood pieces was similar to the DBH of riparian trees (Fig. 4). Median length of alder wood pieces (3.9 m) was greater than legacy and conifer LW (Fig. 3).

The number of alder pieces in channels was significantly positively correlated with the number of dead alder trees in riparian zones. The percentage of red alder LW pieces ranged from 0% to 42%, increasing with increasing amount of standing alder in riparian stands (Fig. 5). However, the number of 3–10 cm diameter alder wood pieces did not significantly correlate with the amount of dead trees because three catchments had large number of dead trees in riparian zones (Fig. 5). No significant relationship between the number of conifer wood pieces in channels and the number of dead trees in riparian zones was found (Fig. 5). The number of LW pieces and detritus accumulations were negatively correlated with bank-full width (LW: $r = -0.58$, $p = 0.01$; FW: $r = -0.65$, $p < 0.01$; detritus accumulation: $r = -0.70$, $p < 0.01$) (Table 2; Fig. 6). However, greater variations in the number of LW and FW pieces and detritus accumulations were found in headwater streams that had bank-full widths < 2 m. The number of LW pieces in upland channel reaches (mean = $0.43 \cdot \text{m}^{-2}$) was greater than that in lowland channel reaches (mean = $0.66 \cdot \text{m}^{-2}$). The volume of LW pieces within bank-full width ranged from 0.01 to $0.16 \text{ m}^3 \cdot \text{m}^{-2}$ in upstream reaches and from 0.01 to

$0.07 \text{ m}^3 \cdot \text{m}^{-2}$ in downstream reaches (Table 2). No significant correlation was found between volume of LW and alder basal area as well as the other channel factors (e.g., channel gradient and bank-full width). Occurrences of mass movement did not significantly affect the number and volumes of wood in channels.

Sediment storage

Sediment volume stored behind LW pieces ranged from 0.0001 to $0.0711 \text{ m}^3 \cdot \text{m}^{-2}$ in upper and lower reaches (Table 2). For all streams, small volumes of sediment were stored behind FW pieces and detritus accumulations (e.g., branches) with mean values of $0.0027 \text{ m}^3 \cdot \text{m}^{-2}$. We found no significant relationship between volume of sediment stored behind LW and FW pieces and the amount of red alder basal area in upland reaches. Volumes of sediment stored behind other channel obstructions such as boulders and bedrock pockets ranged from 0.0001 to $0.0639 \text{ m}^3 \cdot \text{m}^{-2}$ (Table 2). Neither bank-full width nor channel gradients correlated well with stored sediment volume.

For individual sediment storage sites, significantly greater amounts of sediment were stored behind pieces of legacy LW than behind FW pieces and detritus accumulations ($p = 0.02$). Mean volume of total sediment stored behind LW ranged from 0.05 to 0.3 m^3 . Red alder LW pieces, FW, and detritus accumulations stored from 0.05 to 0.1 m^3 sediment (Fig. 7).

Discussion

Factors affecting the distribution and accumulation of wood, detritus, and sediment

Channel bank-full width, rather than riparian stand conditions and management regimes, was found to be the most important factor affecting the distribution and accumulation of wood and detritus in young-growth headwater streams (widths 0.5–4 m) (Fig. 6). The number of LW pieces decreased with increasing channel width ranging from 0.3 to 40 m (Bilby and Ward 1991; Martin 2001; Jackson and Sturm 2002). In contrast, other researchers, studying channels 3–20 m in width, found no significant relationship between wood loadings and channel geometry in managed streams (Beechie and Sibley 1997). Significant effect of bank-full width on wood and detritus accumulation in our small streams was potentially associated with the rapid changes in valley topography (from confined to wide and flat) and stream flow discharge along headwater channels. For LW and FW pieces, relatively small amount of wood pieces were found in small streams (< 2 m in bank-full width) affected by mass movement because wood pieces were transported from upland to lowland reaches (Figs. 6a and 6b). Accumulations of detritus in small upland channel reaches have been associated with low discharge and presence of wood pieces (Brookshire and Dwire 2003).

Other factors, such as current riparian stand conditions, were not significantly associated with the recruitment and accumulations of wood, sediment, and organic matter in channels. Young-growth stands (< 40 years old) produce little LW material (> 10 cm) and have little effect on altering the size distribution of functional LW in channels (Andrus et al. 1988; Fig. 5). Although alder has rapid juvenile growth, the

Fig. 3. Diameter and length of red alder, conifer, and legacy pieces of large wood. Legacy pieces were wood pieces that were recruited from old-growth stands before and during logging in the 1950s. Based on Kruskal–Wallis rank sum test, diameters ($p < 0.01$) and lengths ($p < 0.01$) of alder, conifer, and legacy large wood were significantly different.

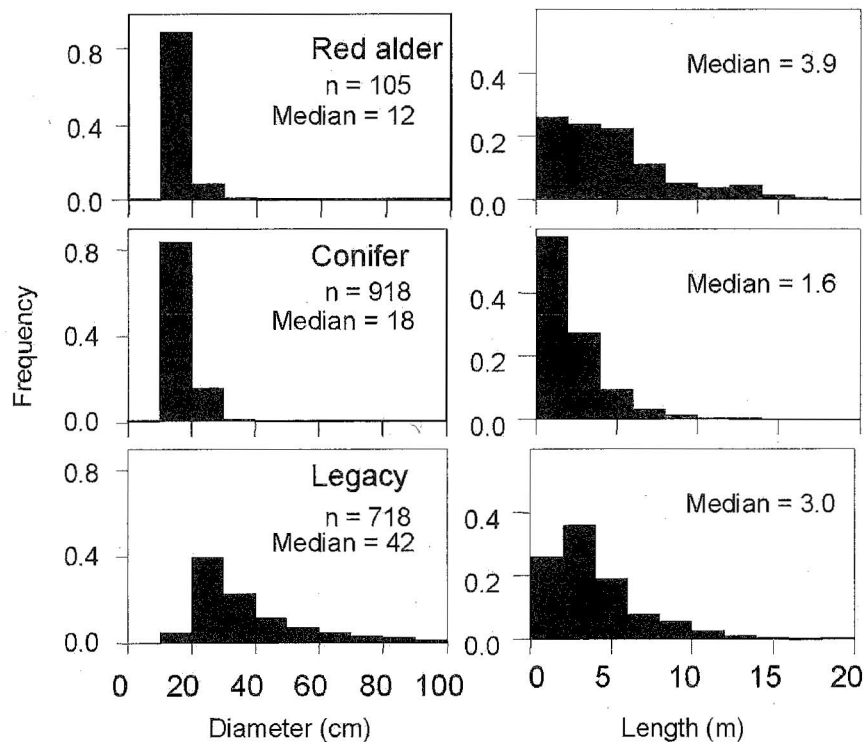
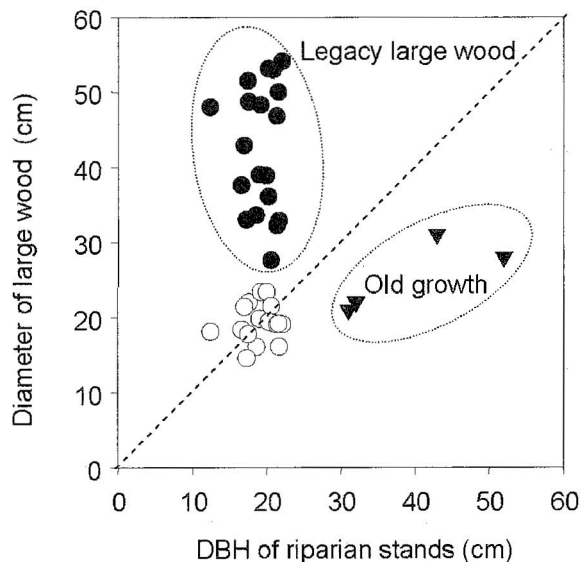


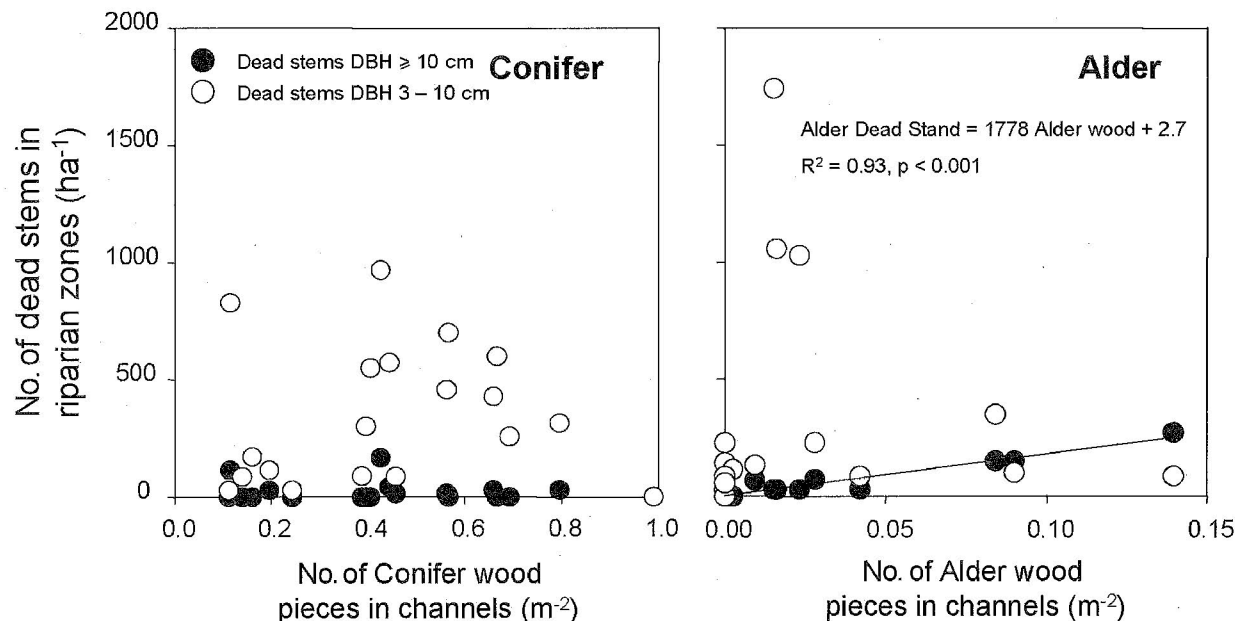
Fig. 4. Relationship between mean DBH of riparian stands (DBH > 10 cm) and diameter of large wood pieces in channels. Open circles indicate relationships between DBH of riparian stands and diameter of all large wood pieces, whereas solid circles show the relationships between DBH of riparian stands and diameter of legacy large wood. Triangles show the relationships between diameter of large wood and riparian stands in undisturbed forests (from Gomi et al. 2001). The broken line represents equal diameters of large wood and mean DBH of riparian stands.



trees that die are relatively small (DeBell and Giordano 1994; Deal et al. 2004). Few large-diameter trees were recruited because there were few large dead red alders or conifers in the riparian stands (Table 2). Orlikowska et al. (2004) found that diameters of dead alder trees were smaller than 10 cm and died standing in headwater riparian zones of southeast Alaska. Grette (1985) found significant increases in volume of alder LW 40 years after logging, whereas increases in conifer LW may take more than 70 years. Based on a numerical model, Beechie et al. (2000) demonstrated that alder LW was replaced by conifer wood pieces 70 years after disturbance in Washington streams. Therefore, more alder wood pieces may be recruited to our study streams during the next 20–30 years when current young alder trees become 60–70 years old. Mixed alder-conifer riparian stands potentially provide larger diameter wood pieces in channels because diameters of conifer trees within mixed conifer-alder riparian stands were greater than ones within pure conifer stands (Table 1) (Deal et al. 2004; Orlikowska et al. 2004).

LW related to past management may mitigate reduced wood and sediment accumulations associated with a change from old-growth to second-growth forest. Most LW pieces (legacy pieces) in headwater streams were recruited during the recent and past timber harvesting in southeast Alaska (Gomi et al. 2001), northern California (Benda et al. 2002), and Appalachian Mountains (Wallace et al. 2001). Jackson and Sturm (2002) showed that the amount of LW in small streams (0.3–3.6 m) varied owing to management history and local channel and hillslope topography in Washington.

Fig. 5. Relationship between number of dead stems in riparian zones and red alder and conifer wood in streams. The number of red alder wood in streams significantly increased with increasing number of dead red alder in riparian zones ($p < 0.001$).



Legacy wood pieces remaining in the channels had greater diameter than wood pieces recruited from riparian young-growth forests. In contrast, diameters of in-channel LW were smaller than riparian diameters in old-growth channels (Fig. 4). Such wood pieces may remain in stream channels more than 50 years after logging. Therefore, past harvesting activities rather than present riparian stand conditions were primarily responsible for the amount of wood pieces and created the most persistent sites of in-channel sediment storage in this study (Fig. 7).

Seasonal changes in leaf litter input alter the accumulations of detritus in channels. Because our stream survey was conducted in July, leaf litter input to streams was relatively small even in riparian stands dominated by alder trees. Sidle (1984) showed that leaf litter input from alder riparian trees was highest in September and October in Bambi Creek, southeast Alaska. Therefore, differences in detritus accumulations between alder- and conifer-dominated riparian stands may be small and difficult to detect (Fig. 6c). Quicker decomposition and fragmentation of alder (Anderson et al. 1978; Bilby et al. 1999) may also have affected accumulation of wood and detritus in our headwater channels.

Interaction of streams and riparian zones: a conceptual model

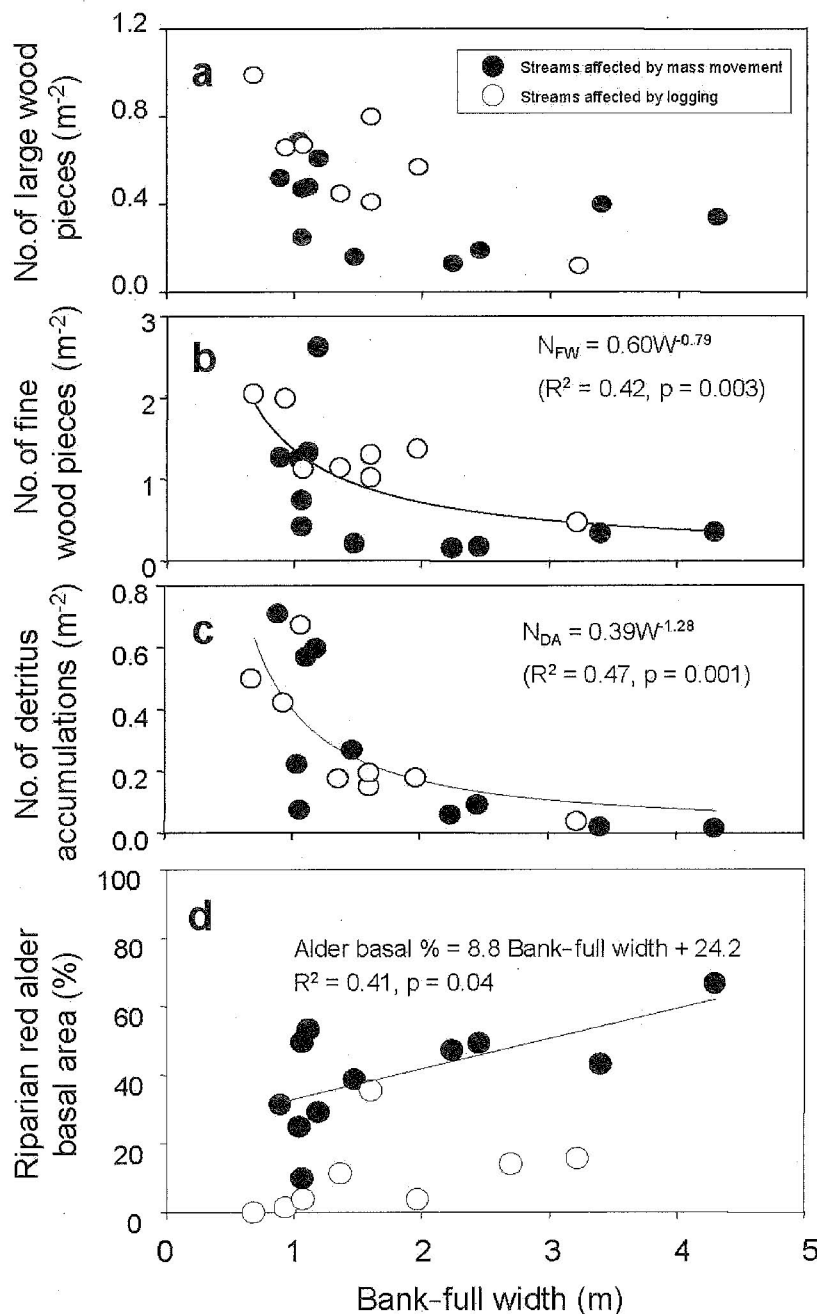
Based on our results, we present a conceptual model for factors associated with wood and detritus accumulations in upland and lowland reaches of headwater streams (Fig. 8). We define the lower portions of upland reaches as transitional reaches (channel gradient 10%–20%) because of the gradual changes of channel and valley morphology and resultant wood and detritus accumulations (Gomi et al. 2004). In the River Continuum Concept, Vannote et al. (1980) stated that wood and organic matter are retained more in headwater streams than in downstream reaches within large watershed

systems (10–100 km² catchment area). However, our findings suggested that wood and organic matter retention was significantly changed along headwater channels within even short channel reaches (up to 700 m of channel length) and small ranges of channel width (0.5–4 m) owing to changes in stream flow and channel and valley morphology. Gomi et al. (2003) showed that, because of changes in channel steps associated with wood pieces, channel reach types (e.g., cascade, step-pool, and pool-riffle) change noticeably along headwater streams within relatively short distances along headwaters of southeast Alaska. Therefore, regarding the wood, detritus, and sediment accumulations, changes in the interactions between streams and riparian zones may be more variable even within headwater systems as demonstrated in the following conceptual model.

Upland reach

The uppermost reach (channel gradient = 20%) is typically constrained by the adjacent hillslopes (Fig. 8), is fishless (Bryant et al. 2004), and is typically affected by scour and runout of mass movement (Gomi et al. 2004). Significantly more red alder basal area is found in streams impacted by mass movements versus those without mass movements in upland second-growth forests (Johnson and Edwards 2002). Red alder was much more concentrated immediately adjacent to streams (Orlikowska et al. 2004). Wood pieces are accumulated more effectively because of the smaller transport capacity (discharge) (Keller and Swanson 1979; Bilby and Ward 1989; Webster 1994). Here, LW and FW pieces form channel steps (Bilby 1981; Gomi et al. 2003) where wood and detritus are accumulated and stored in channels until such materials are fragmented, decomposed, and transported (Brookshire and Dwire 2003). Accumulation of detritus may alter community structure and habitat for macroinvertebrates in smaller streams (Anderson

Fig. 6. Relationship between bank-full width and (a) number of large wood pieces, (b) number of fine wood pieces, (c) detritus accumulations, and (d) the amount of riparian red alder.



et al. 1978; Richardson 1992; Hernandez et al. 2005), providing processed organic matter and terrestrial and aquatic organisms to lowland fish-bearing reaches (Wipfli and Gregovich 2002; Wipfli and Musslewhite 2004).

Transitional reach

Transitional reaches, located on the foot of hillslopes in U-shaped valleys, typically have lower gradients (ranging from 10% to 20%) compared with the upland reaches and have an increase in stream discharge owing to increased drainage area and converged groundwater flow from hill-

slopes (Fig. 8a). These reaches typically have resident fish at the upper extent of fish habitats for juvenile coho salmon, Dolly Varden, and steelhead trout depending on the distribution of pools (Bryant et al. 2004). These reaches may vary considerably owing to sediment supply from the upper reaches. For example, where there is greater sediment supply owing to mass movements, mineral soil is exposed or deposited and red alder regeneration is enhanced. Disturbed areas may be constrained by hillslopes depending on valley topography. Increasing discharge in this reach may transport wood and organic matter more effectively.

Fig. 7. Mean volume of sediment stored behind total, red alder, and legacy large wood pieces as well as fine wood and detritus accumulations. The volume of sediment stored behind legacy large wood was significantly greater than the volume of sediment stored by fine wood pieces and detritus accumulations.

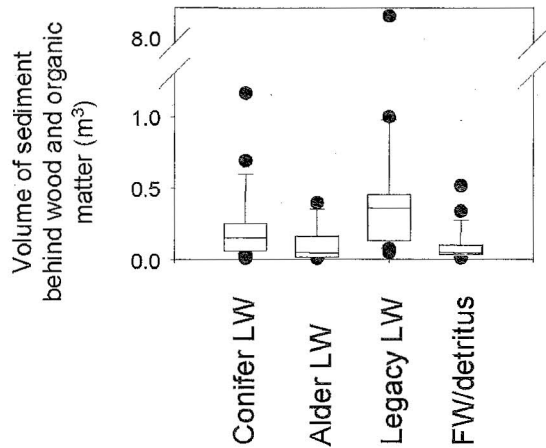
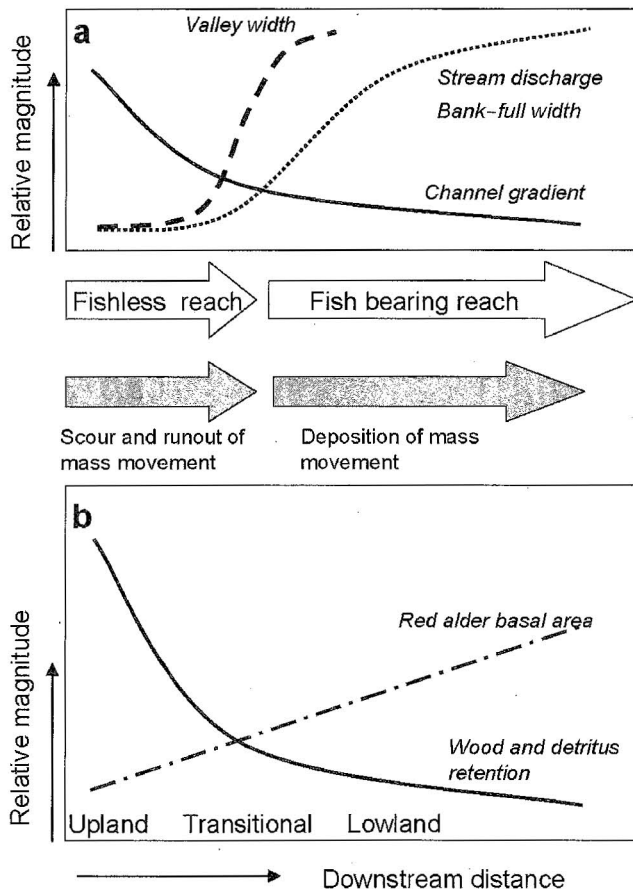


Fig. 8. Conceptual model for the factors of wood and detritus accumulations relative to the amount of red alder in riparian zones. (a) Characteristics of physical parameters such as valley configurations, channel gradients, bank-full width, and absolute discharge along headwater streams. (b) Changes in the amount of red alder and woody debris retentions from upper to lower reaches. Data of fish distribution are from Bryant et al. (2004).



Lowland reach

Downstream reaches, typically located at the bottom of U-shape glacial valleys (flood plain), have low gradients ($\approx 10\%$) and generally are not confined by side slopes (Fig. 8a). These reaches are often important habitat for juvenile salmonids (e.g., winter rearing) (Bryant et al. 2004). In these areas, various sizes of debris fans and log jams are formed as a result of deposition of sediment transported from upstream reaches and provide sites for red alder establishment (Johnson et al. 2000; Gomi et al. 2004) (Fig. 8b). In these low-gradient reaches, soils were often disturbed by tractor logging during the 1950s (D.N. Swanston, personal communication). Relatively greater percentages of alder riparian trees are found (Fig. 8b) and more terrestrial prey for juvenile fishes may be available (Wipfli 1997; Allan et al. 2003). Most LW and FW pieces recruited from red alder and conifer trees may be transported farther downstream because of greater channel width and greater discharge. Alder riparian trees provide significant sources of nutrients and suspended particulate organic matter (Johnson and Edwards 2002; Yolk et al. 2003). Bank erosion may cause more tree mortality and subsequent wood recruitment in lowland reaches.

Summary and conclusions

We investigated accumulation and distribution of wood pieces and sediment in headwater streams with respect to the amount of red alder in young-growth riparian forests. We found that retention of wood and detritus varied spatially with changes in geomorphic conditions. Findings of this study were summarized with stream and riparian conditions in the following five ways: (i) the amount of red alder in riparian zones is directly affected by the level of mass movement and timber harvesting disturbance, (ii) more red alder LW was found in streams with more riparian alder, (iii) more wood and detritus were retained in streams with smaller channel widths (upland reaches) than in larger channels (lowland reaches) regardless of riparian stand condition and mass movement, (iv) legacy LW pieces provide sites for more sediment storage in headwater channels, and (v) effects of current riparian stand conditions (alder-conifer mixture) on wood and organic matter accumulations were masked by past management, mass movement, and channel properties.

A component of alder within young-growth riparian forests may benefit both wood production and biological recovery in disturbed headwater stream channels. Alder FW and detritus accumulations in Maybeso headwater streams currently support food and energy sources for stream biota in headwaters and their downstream systems (Piccolo and Wipfli 2002; Wipfli and Musslewhite 2004). However, the limited large pieces of legacy wood continue to provide the most useful physical structures for retaining sediment and creating pools. Over the next 50 years, the recruitment of new and LW pieces from young-growth forest and decay of legacy wood pieces may alter the accumulation of organic matter and change sediment storage (Hennon et al. 2002). Given enough time, mixed red alder - conifer forests will produce large-diameter conifer trees (Deal et al. 2004). These large-diameter conifer trees from second-growth forest should play a critical role in creating diverse structures in stream channels (e.g., steps, pools, and sediment storage) and improve habitat quality for fish and macroinvertebrates.

when larger trees in these stands began to die. Such temporal changes together with the spatial variation of wood, detritus, and sediment accumulations and distribution along headwater channels provide for diverse and unique characteristics of headwater systems within channel networks.

Acknowledgements

This research was funded by the Wood Compatibility Initiative, USDA Pacific Northwest Research Station. T.O. was supported by the JST/CREST project during a period for revising and finalizing an earlier draft of this manuscript. We thank Rick Edwards, Rick Woodsmith, Christine May, Dan Moore, John Richardson, Roy Sidle, and Sohei Kobayashi for their insightful and helpful comments on an earlier draft of this manuscript. We thank Kim Obermeyer and Yuho Okada for their assistance with fieldwork. The manuscript was significantly improved with suggestions and comments from two anonymous reviewers and an associate editor.

References

- Alaback, P.B., and Sidle, R.C. 1986. Biomass, structure, and nutrients of riparian vegetation on a small watershed on Chichkof Island; southeast Alaska. *In* Watershed research perspectives. Edited by D.L. Correll. Smithsonian Institution Press, Edgewater, Md. pp. 135-165.
- Allan, J.D., Wipfli, M.S., Caouette, J.P., Prussian, A., and Rodgers, J. 2003. Influence of streamside vegetation on terrestrial invertebrate subsidies to salmonid food webs. *Can. J. Fish. Aquat. Sci.* 60: 309-320.
- Anderson, N.H., Sedell, J.R., Roberts, L.M., and Triska, F.J. 1978. The role of aquatic invertebrates in processing of wood debris in coniferous forest streams. *Am. Midl. Nat.* 100: 64-82.
- Andrus, c.w., Long, B.A., and Froelich, H.A. 1988. Woody debris and its contribution to pool formation in a coastal stream 50 years after logging. *Can. J. Fish. Aquat. Sci.* 45: 2080-2086.
- Beechie, T.J., and Sibley, T.H. 1997. Relationships between channel characterizes, woody debris, and fish habitat in northwestern Washington streams. *Trans. Am. Fish. Soc.* 126: 217-229.
- Beechie, T.J., Pess, G., Kennard, P., Bilby, R.E., and Bolton, S. 2000. Modeling recovery rates and pathways for woody debris recruitment in northwestern Washington streams. *N. Am. J. Fish. Manage.* 20: 436-452.
- Benda, L.E., Bigelow, P., and Worsley, T.M. 2002. Recruitment of wood to stream in old-growth and second-growth redwood forests, northern California, U.S.A. *Can. J. For. Res.* 32: 1460-1477.
- Bilby, R.E. 1981. Role of organic debris dams in regulating the export of dissolves and particulate matter from a forested watershed. *Ecology*, 62: 1234-1275.
- Bilby, R.E., and Ward, J.W. 1989. Change in characteristics and function of woody debris with increasing size of stream in western Washington. *Trans. Am. Fish. Soc.* 118: 368-378.
- Bilby, R.E., and Ward, J.W. 1991. Characteristics and function of large woody debris in streams draining old growth, clear-cut, and 2nd-growth forest in southwestern Washington. *Can. J. Fish. Aquat. Sci.* 48: 2499-2508.
- Bilby, R.E., Heffner, J.T., Fransen, B.R., Ward, J.W., and Bisson, P.A. 1999. Effects of immersion in water on deterioration of wood from five species of trees used for habitat enhancement projects. *N. Am. J. Fish. Manage.* 19: 687-695.
- Brookshire, J.E.N., and Dwire, K.A. 2003. Controls on patterns of coarse organic particle retention in headwater streams. *J. North Am. Benthol. Soc.* 22: 17-34.
- Bryant, M.D., Zimonas, N., and Wright, B. 2004. Salmonids on the fringe: distribution, habitat use, and response of salmonids to upslope riparian forest composition in high gradient headwater streams, southeast Alaska. *Trans. Am. Fish. Soc.* 133: 1529-1538.
- Casas, J.J. 1997. Invertebrate assemblages associated with plant debris in a blackwater of a mountain stream: natural leaf packs vs. debris dam. *J. Freshw. Ecol.* 12: 39-49.
- Cederholm, C.J., Bilby, R.E., Bisson, P.A., Bumstead, T.W., Fransen, B.R., Scarlett, W.J., and Ward, J.W. 1997. Response of juvenile coho salmon and steelhead to placement of large woody debris in a coastal Washington stream. *N. Am. J. Fish. Manage.* 17: 947-963.
- Deal, R.L., Hennon, P.E., Orlikowska, E.H., and D'Amore, D.V. 2004. Stand dynamics of mixed red alder-conifer forests of southeast Alaska. *Can. J. For. Res.* 34: 969-980.
- DeBell, D.S., and Giordano, P.A. 1994. Growth patterns of red alder. *In* The biology and management of red alder. Edited by D.E. Hibbs, D.S. DeBell, and R.F. Tarrant. Oregon State University Press, Corvallis, Ore. pp. 116-130.
- Eberlein, G.D., Churkin, M., Carter, C., Berg, B.C., and Ovenshine, A.T. 1983. Geology of the Craig Quadrangle, Alaska. *U.S. Geol. Surv. Open-File Rep.* 93-91.
- Gomi, T., Sidle, S.C., Bryant, M.D., and Woodsmith, R.D. 2001. Characteristics of woody debris and sediment in headwater streams, southeast Alaska. *Can. J. For. Res.* 31: 1386-1399.
- Gomi, T., Sidle, R.C., and Richardson, J.S. 2002. Understanding processes and downstream linkages in headwater systems. *BioScience*, 52: 905-916.
- Gomi, T., Sidle, R.C., Woodsmith, R.D., and Bryant, M.D. 2003. Characteristics of channel steps and reach morphology in headwater streams, southeast Alaska. *Geomorphology*, 51: 225-242.
- Gomi, T., Sidle, R.C., and Swanson, D.N. 2004. Hydrogeomorphic linkages of sediment transport in headwater streams, Maybeso Experimental Forest, southeast Alaska. *Hydro. Processes*, 18: 667-683.
- Gregory, S.Y., Swanson, F.J., McKee, W.A., and Cummins, K.W. 1991. An ecosystems perspective of riparian zones. *BioScience*, 41: 540-551.
- Grette, G.B. 1985. The role of organic debris in juvenile salmonid rearing habitat in small streams. M.S. thesis, University of Washington, Seattle, Wash.
- Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.Y., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, I.R., Lienkaemper, G.W., Cromack, K., and Cummins, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. *Adv. Ecol. Res.* 15: 133-302.
- Harrington, C.A., Zasada, J.C., and Allen, E.A. 1994. Biology of red alder (*Alnus rubra* Bong.). *In* The biology and management of red alder. Edited by D.E. Hibbs, D.S. DeBell, and R.F. Tarrant. Oregon State University Press, Corvallis, Ore. pp. 3-22.
- Hedman, C.W., Van Lear, D.H., and Swank, W.T. 1996. In-stream large woody debris loading and riparian forest serial stage associations in the southern Appalachian Mountains. *Can. J. For. Res.* 26: 1218-1227.
- Hennon, P., Wipfli, M., Deal, R., De Santo, T., Johnson, A., Hennon, P., Schultz, M., Hanley, T., Orlikowska, E., Gomi, T., Bryant, M., and Edwards, R. 2002. Mixed alder-conifer forests: managing upland ecosystems in southeast Alaska for wood products, wildlife, and fish. *In* Congruent management of multiple resources: Proceedings of the Wood Compatibility Initiative Workshop, 4-7 December 2001, Stevenson, Wash. Edited by A.C. Johnson, R.W.

- Haynes, and RA Monserud. USDA For. Servo Gen. Tech. Pap. PNW-GTR-563. pp. 51-58.
- Hernandez, O., Meritt, R.W., and Wipfli, M.S. 2005. Benthic invertebrate community structure is influenced by forest succession after clearcut logging in southeast Alaska. *Hydrobiologia*, 533: 45-59.
- Hibbs, D.E., and Giordano, P.A. 1996. Vegetation characteristics of alder-dominated riparian buffer strips in Oregon Coast Range streams. *Northwest Sci.* 70: 213-222.
- Jackson, C.R., and Sturm, C.A. 2002. Woody debris and channel morphology in first- and second-order forested channels in Washington's coast ranges. *Water Resour. Res.* 38: 1177, doi: 10.1029/2001WR001138.
- Johnson, A.C., and Edwards, R.T. 2002. Physical and chemical processes in headwater channels with red alder. *In* Congruent management of multiple resources: Proceedings of the Wood Compatibility Initiative Workshop, 4-7 December 2001, Stevenson, Wash. *Edited by* A.C. Johnson, R.W. Haynes, and R.A. Monserud. USDA For. Servo Gen. Tech. Pap. PNW-GTR-563. pp. 101-108.
- Johnson, A.C., Swanston, D.N., and McGee, K.E. 2000. Landslide initiation, runoff, and deposition within clearcuts and old-growth forests of Alaska. *J. Am. Water Resour. Assoc.* 36: 1-14.
- Keller, E.A., and Swanson, F.J. 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surf. Processes Landforms*, 4: 361-380.
- Martin, D.J. 2001. The influence of geomorphic factors and geographical region on large woody debris loading and fish habitat in Alaska coastal streams. *N. Am. J. Fish. Manage.* 21: 429-440.
- May, C.L., and Gresswell, R.E. 2003. Processes and rates of sediment and wood accumulation in headwater stream of the Oregon Coast Range, U.S.A. *Earth Surf. Processes Landforms*, 28: 409-424.
- Meehan, W.R., Farr, W.A., Bishop, D.M., and Patrie, J.H. 1969. Effects of clear-cutting on salmon habitat of two southeast Alaska streams. *US For. Servo Res. Pap.* PNW-RP-82.
- Minore, D., and Weatherly, H.G. 1994. Riparian trees, shrubs, and forest regeneration in the coastal mountain in Oregon. *New For.* 8: 249-263.
- Moore, R.D., and Richardson, J.S. 2003. Progress towards understanding the structure, function, and ecological significance of small stream channels and their riparian zones. *Can. J. For. Res.* 33: 1349-1351.
- Orlikowska, E.W., Deal, R.L., Hennon, P.E., and Wipfli, M.S. 2004. The role of red alder in riparian forest structure along headwater streams in southeastern Alaska. *Northwest Sci.* 78: 111-123.
- Piccolo, J.J., and Wipfli, M.S. 2002. Does red alder (*Alnus rubra*) in upland riparian forests elevate macroinvertebrates and detritus export from headwater streams to downstream habitats in southeastern Alaska? *Can. J. Fish. Aquat. Sci.* 59: 503-513.
- Ralph, S.C., Poole, G.C., Conquest, L.L., and Naiman, R.J. 1994. Stream channel condition and in-stream habitat in logged and unlogged basins of western Washington. *Can. J. Fish. Aquat. Sci.* 51: 37-51.
- Richardson, J.S. 1992. Coarse particulate detritus dynamics in small, montane streams of southwestern British Columbia. *Can. J. Fish. Aquat. Sci.* 49: 337-346.
- Richardson, J.S., Bilby, R.E., and Bondar, C.A. 2005. Organic matter dynamics in small streams of the Pacific Northwest. *J. Am. Water Resour. Assoc.* 41: 921-934.
- Rot, B.W., Naiman, R.J., and Bilby, R.E. 2000. Stream channel configuration, landform, and riparian forest structure in the Cascade Mountains, Washington. *Can. J. Fish. Aquat. Sci.* 57: 699-707.
- Sidle, R.C. 1984. Seasonal pattern of allochthonous debris in three riparian zones of a coastal Alaska drainage. *In* Watershed research prospective. *Edited by* D.L. Correll. Smithsonian Institution Press, Washington, D.C. pp. 283-304.
- Swanston, D.N., and Marion, D.A. 1991. Landslide response to timber harvest in southeast Alaska. *In* Proceedings of the Fifth Interagency Sedimentation Conference. Vol. 10. Federal Energy Regulatory Commission, Las Vegas, Nev. pp. 49-58.
- Vannote, R.L., Minshall, G., Cummins, K.W., Sedell, J.R., and Cushing, C.E. 1980. The River Continuum Concept. *Can. J. Fish. Aquat. Sci.* 37: 130-137.
- Venables, W.N., and Ripley, B.D. 1997. Modern applied statistics with S-PLUS. Springer, New York.
- Volk, C.J., Kiffney, P.M., and Edmonds, R.L. 2003. Role of riparian red alder in the nutrient dynamics of coastal streams of the Olympic Peninsula, Washington, USA. *In* Nutrient in salmonid ecosystems: sustaining production and biodiversity. *Edited by* J.G. Stockner. *Am. Fish. Soc. Symp.* 34: 213-225.
- Wallace, J.B., Webster, J.R., Eggert, S.L., Meyer, J.L., and Siler, E.R. 2001. Large woody debris in a headwater stream: long-term legacies of forest disturbance. *Int. Rev. Gesamten Hydrobiol.* 86: 501-513.
- Webster, J.R., Covich, A.P., Tank, J.L., and Crockett, T.V. 1994. Retention of coarse organic particles in streams in the south Appalachian Mountains. *J. North Am. Benthol. Soc.* 13: 140-150.
- Wipfli, M.S. 1997. Terrestrial invertebrates as salmonid prey and nitrogen sources in streams: contrasting old-growth and young-growth riparian forests in southeastern Alaska, U.S.A. *Can. J. Fish. Aquat. Sci.* 54: 1259-1269.
- Wipfli, M.S., and Gregovich, D.P. 2002. Invertebrates and detritus export from fishless headwater streams in southeastern Alaska: implications for downstream salmonid production. *Freshw. Biol.* 47: 957-970.
- Wipfli, M.S., and Musslewhite, I. 2004. Density of red alder (*Alnus rubra*) in headwaters influences invertebrate and detritus subsidies to downstream fish habitat in Alaska. *Hydrobiologia*, 520: 153-163.
- Wipfli, M.S., Deal, R.L., Hennon, P.E., Johnson, A.C., Edwards, R.T., De Santo, T.L., Gomi, T., Orlikowska, E.H., Bryant, M.D., Schultz, M.A., LeSage, C., Kimbirauskus, R., and D'Amore, D.V. 2003. Compatible management of red alder - conifer ecosystems in southeastern Alaska. *In* Compatible forest management. *Edited by* R.A. Monserud, R.W. Haynes, and A.C. Johnson. Kluwer Academic Publishers, Dordrecht, Netherlands. pp. 55-84.