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PROCESSES AND RATES OF SEDIMENT AND WOOD ACCUMULATION IN HEADWATER STREAMS OF THE OREGON COAST RANGE, USA

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ABSTRACT

Channels that have been scoured to bedrock by debris flows provide unique opportunities to calculate the rate of sediment and wood accumulation in low-order streams, to understand the temporal succession of channel morphology following disturbance, and to make inferences about processes associated with input and transport of sediment. Dendrochronology was used to estimate the time since the previous debris flow and the time since the last stand-replacement fire in unlogged basins in the central Coast Range of Oregon. Debris flow activity increased 42 per cent above the background rate in the decades immediately following the last wildfire. Changes in wood and sediment storage were quantified for 13 streams that ranged from 4 to 144 years since the previous debris flow. The volume of wood and sediment in the channel, and the length of channel with exposed bedrock, were strongly correlated with the time since the previous debris flow. Wood increased the storage capacity of the channel and trapped the majority of the sediment in these steep headwater streams. In the absence of wood, channels that have been scoured to bedrock by a debris flow may lack the capacity to store sediment and could persist in a bedrock state for an extended period of time. With an adequate supply of wood, low-order channels have the potential of storing large volumes of sediment in the interval between debris flows and can function as one of the dominant storage reservoirs for sediment in mountainous terrain.

KEY WORDS: debris flows; sedimentation; large wood; dendrochronology; bedrock streams

INTRODUCTION

First- and second-order streams (Strahler, 1964; referred to hereafter as low-order streams) can represent 60–80 per cent of the cumulative channel length in mountainous terrain (Schumm, 1956; Shreve, 1969). Because of their abundance and distribution throughout the channel network, low-order streams are one of the primary pathways for routing water, sediment, and wood from hillslopes to higher-order rivers. Many low-order streams in the Oregon Coast Range are naturally prone to episodic disturbance by debris flows because they drain steep, landslide-prone hillslopes. Past studies in the Oregon Cascade Range (Swanson *et al.*, 1982; Grant and Wolff, 1991) and in central Idaho (Megahan and Nowlin, 1976) indicate that fluvial transport of sediment and wood is minimal during the interval between debris flows. Instead, many low-order streams undergo long periods of net increase in the storage of sediment and wood that is punctuated by episodic transport by debris flows (Dietrich and Dunne, 1978; Swanson *et al.*, 1982). Sediment that is entrained as a debris flow travels through low-order channels can account for over 80 per cent of the volume of debris flow deposits (May, 2002).

Unlike larger rivers, sediment storage sites, such as point bars and floodplains, are absent in steep low-order streams because they are tightly constrained by the surrounding hillslopes. Thus, large wood may account for a much greater portion of the total sediment in storage in headwater streams (Keller and Swanson, 1979). For example, large wood stored 49 per cent of the sediment in seven small Idaho watersheds (Megahan, 1982), and 87 per cent of the sediment in a small stream reach in New Hampshire (Bilby, 1981). By increasing the

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sediment storage capacity of the channel, large wood buffers the sedimentation impacts on downstream reaches when pulses of sediment enter headwater streams (Swanson and Lienkaemper, 1978; Lancaster *et al.*, 2001).

Debris flows transport sediment and wood stored in low-order channels and leave behind an erosional zone that is typically scoured to bedrock (Swanson and Lienkaemper, 1978; May, 2002). The erosion of the channel to bedrock provides a unique opportunity to calculate the rate of wood and sediment accumulation, and to gain insight into the processes that refill the channel with sediment and wood in the interval between debris flows. In low-order streams, the size of wood is typically large in relation to the size of the channel (Bilby and Ward, 1989; Bilby and Bisson, 1998), and it can be assumed that fluvial processes transport very few pieces of wood in the interval between debris flows. Conversely, the sediment transport capacity of the channel may be high immediately following a debris flow because bedrock channels are typically straight, steep, and have a high hydraulic radius and low roughness. Therefore, immobile pieces of wood can form a physical obstruction to sediment transport that may be critical for sediment accumulation in this portion of the drainage network.

The goal of this study was to investigate changes in sediment and wood storage volumes, and associated changes in channel morphology, in low-order streams that are prone to erosion by debris flows. We used a space-for-time substitution approach to align spatially separated states along a temporal sequence (Welch, 1970). Specific objectives were to: (1) quantify the rate of wood and sediment accumulation in second-order streams that are prone to erosion by debris flows; (2) identify the mechanisms for storing sediment in high-gradient, low-roughness channels; and (3) assess the relative importance of debris-flow-prone tributaries as storage reservoirs for sediment in the drainage basins.

STUDY AREA

Two third-order basins with a minimal history of timber harvest and road construction were selected for this study (Figure 1; Table I). Sediment production and transport processes in the basins were considered typical of debris flow terrain in the central Coast Range of Oregon. Skate Creek has a drainage area of 2·5 km^2 and

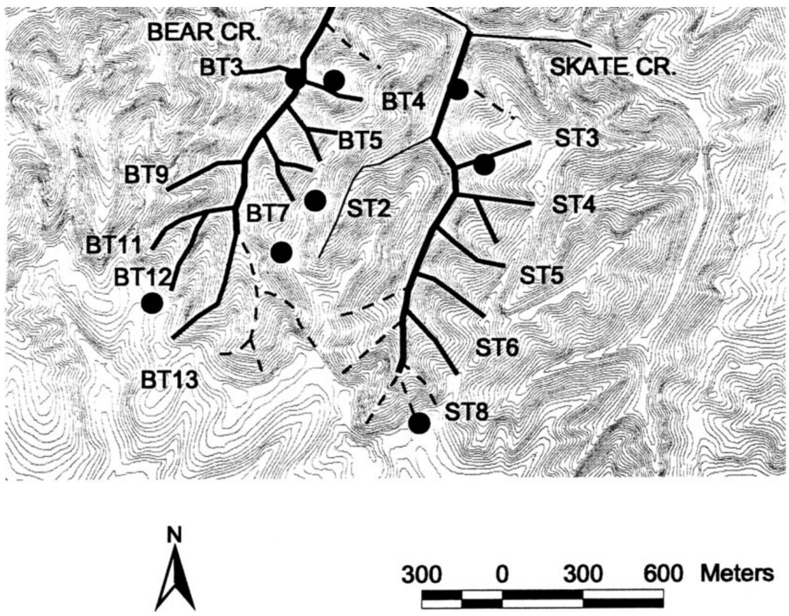

Figure 1. Site map of Skate and Bear Creeks, Siuslaw River drainage in the central Oregon Coast Range. Dark solid lines represent channels investigated for wood and sediment storage. Dashed lines represent colluvial tributaries impacted by timber harvest and not investigated. Thin solid line (ST2) is only tributary with no evidence of delivering debris flows to the mainstem. Numerous first-order channels throughout the network are not highlighted and are not well represented on low-resolution topographic data. Solid circles represent sample sites for the dendrochronology-based fire history reconstruction. Contour interval = 10 m

Table I. Channel and basin characteristics of Skate and Bear Creeks

Tributary	Total channel length (m)	Erosional zone length (m)	Erosional zone drainage area at downstream end (km^2)	Average erosional zone slope (%)	Average valley floor width (m)
Skate T3	384	344	0·15	29	4·0
Skate T4	714	584	0·15	30	3·9
Skate T5	313	265	0·11	25	3·4
Skate T6	354	296	0·09	32	3·3
Skate T8	290	290	0·12	38	4·5
Bear T3	252	215	0·06	32	4·4
Bear T4	445	254	0·08	32	5·0
Bear T5	315	239	0·08	34	3·2
Bear T7	486	389	0·09	35	4·3
Bear T9	514	462	0·09	25	4·4
Bear T11	399	242	0·15	22	4·8
Bear T12	420	420	0·11	26	4·8
Bear T13	489	261	0·20	41	2·8

Bear Creek has a drainage area of 2·3 km^2; both are located in the Siuslaw River drainage. A ridge-top road and small clearcut units are located at the upper extent of both basins. Tributaries that were influenced by timber harvest activities were not investigated.

The study basins are underlain by Tertiary marine sedimentary rocks of the Tyee Formation (Baldwin, 1964). The Tyee Formation is composed of massive, rhythmically bedded sandstones with interbeds of siltstones and mudstones. The drainage network is characterized by a dense, dendritic drainage pattern in first- and second-order streams that drain short, steep hillslopes. The low-elevation (<500 m) mountains are unglaciated and have a topography similar to the 'ridge and ravine topography' described by Hack (1960). The soils are well drained and range from loams to clay loams.

The dominant overstorey species in the forest are Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*), and the basins are located in the western hemlock zone (Franklin and Dyrness, 1973). These stands naturally regenerated after historic fires in the 1850s and were never harvested for timber. Red alder (*Alnus rubra*) is typically found in riparian areas, or in areas of recent disturbance, and is the most common deciduous species. A thick ground cover of shrubs consists mostly of salmonberry (*Rubus spectabilis*), thimbleberry (*Rubus parviflorus*), vine maple (*Acer circinatum*), swordfern (*Polystichum munitum*), salal (*Gaultheria shallon*), and huckleberry (*Vaccinium parvifolium*). These shrubs rapidly colonize landslide scars, and the dense understorey significantly limited visibility.

METHODS

Second-order channels prone to debris flows were identified by the presence of either a current or remnant depositional feature at the tributary junction with the mainstem. The stratigraphy of debris flow deposits was differentiated from alluvial deposits by the dominance of poorly sorted, angular colluvium in the former. All of the channels we investigated were also predicted to deliver debris flows to the mainstem river by an empirical model based on tributary junction angle and channel gradient (Benda and Cundy, 1990).

The erosional zone of the channel was defined as the portion of the second-order channel length that had a high likelihood of being scoured of material by a previous debris flow. Prior research on 53 recent debris flows in this area found that >80 per cent of the channel reaches investigated that exceeded 20 per cent slope were scoured by debris flow (May, 2002). Slopes <20 per cent were subject to both scour and deposition by debris flows. The downstream extent of the erosional zone was identified in the field by ascending the second-order channels until a consistent slope of >20 per cent was encountered, or earlier if continuous reaches of exposed bedrock were present. Surveys continued up the channel until a pair of first-order channels was encountered at the upper extent of the second-order channel. Stream-order classification was based on a valley network defined by areas of convergent topography on 10 m resolution digital elevation models.

Time since the previous debris flow was estimated by ageing trees currently growing on the valley floor of channels in the erosional zone. Trees in the depositional zone were not dated because of a greater likelihood that older trees survived the previous debris flow. Tree cores were extracted <1 m above the base of the tree on the uphill side, with a 46 cm long increment bore. Cores were air-dried, mounted, planed, and sanded until cell structure was clearly visible. The time since the previous debris flow was expressed in years before 2000. Additional years were added to the tree ring count to correct for the number of years required for the tree to grow to the height at which it was sampled (Agee, 1993). The oldest date acquired for a particular channel was used in the analysis; however, dates can be considered only a minimum time since the previous debris flow because limited information is available on the time required for tree establishment or for successional lags among species. By estimating only a minimum time since the last debris flow, the process rates that we report may be overestimated. Additional error is also inherent in estimating precise dates from tree core samples. The most common source of error in our analysis was underestimation of the actual age when the exact centre point of the tree was not encountered during sampling; thus, the first few years of growth may have been missed.

The time since the previous stand-replacement fire was investigated by coring trees at eight sample sites in the study basins. Two distinct size classes of trees were observed on aerial photographs. The larger size class of trees was located in the low elevation valley floors, and the smaller size class was located on mid- and upper-hillslope positions. This pattern was consistent in both Bear and Skate drainages. Sampling focused on four topographic positions: (1) ridge tops, (2) upper-slope positions where landslides initiated debris flows, (3) mid-slope positions that approximated the runout zone of debris flows, and (4) along the low-elevation valley floors of Bear and Skate Creeks. Two sample sites were located in each zone (Figure 1), and four to six trees were sampled at each site. A minimum number of trees were sampled because an intensive fire reconstruction study was previously conducted in the vicinity (Impara, 1997). Impara (1997) documented a massive, stand-replacement wildfire that was likely to have burned through the uplands in our study basins. Preliminary investigations of tree ages on the hillslopes found a strong correspondence of ages with the 1850s wildfire, and an extremely low variance in tree age on the uplands provided further evidence that a single stand-replacement wildfire had occurred.

Measurements of wood and sediment accumulation

The volume of wood was quantified by surveying the entire length of the second-order channel in each tributary. Pieces of wood with an average diameter >20 cm and length >2 m were measured. Only pieces that were in contact with the channel or valley floor were measured, and wood that was suspended >2 m above the channel was not recorded. The volume of each piece was calculated as a cylinder using the average diameter and total piece length. Pieces of wood that were actively storing sediment were documented.

Sediment accumulations were measured if they were at least equal in length to the active channel width. The volume of sediment was estimated by measuring the valley floor width, the length of the sediment accumulation, and the average thickness of the sediment accumulation above bedrock. For discrete deposits formed behind obstructions, the volume of the sediment was calculated as a wedge, assuming a constant bedrock slope beneath the deposit. For more continuous accumulations of sediment, a rectangular volume of sediment was calculated, also assuming a constant bedrock slope beneath the deposit. Because patches of bedrock were frequently present and layers of sediment were typically thin and discrete, it was possible to reliably estimate sediment depth.

The particle size of the surface layer of sediment was assessed by visually estimating the proportion of the streambed covered by fine sediment (<2 mm), gravel (2–64 mm), cobble (65–256 mm), boulder (>256 mm), and bedrock in each sediment accumulation patch. Field observations indicated the development of an armour layer; therefore, the proportion of fine sediment stored in these channels was underestimated by observations of the surface layer. Similarly, Benda and Dunne (1987) observed that below a surface pavement, the texture of sediments in low-order channels consisted of colluvium that had undergone little to no sorting by fluvial transport.

Sediment accumulation rates were calculated only for the erosional zone of the channel; however, sediment storage throughout the Skate Creek basin was investigated. Sediment storage was measured in all second-and third-order channels in the unlogged portion of Skate Creek (Figure 1). Sediment storage could not be measured in tributaries that had been harvested for timber in previous decades because the abundance of logging debris substantially impaired access to the streambed, and sediment depth could not be reliably estimated. The volume of sediment stored in terraces along the mainstem of Skate Creek was calculated as a trapezoid with the volume of the bank-full channel removed. The height of the terrace above bedrock in the streambed, terrace width on each side of the channel, and the hillslope angles were measured at 50 m intervals. The perimeter, height above the streambed, and the distance from the apex of the fan (i.e. the hillslope constriction of the tributary) to the mainstem channel edge was measured at each debris flow fan. Fan volume was calculated as half an ellipse because this shape was a good approximation of the actual, two-dimensional shape of fans developed within the constraints of a relatively narrow valley floor. This calculation underestimated the actual volume because the sloping surface of the fan was not accounted for.

Predicting sediment input

Observations of sediment storage in channels can be used to make inferences about input and transport processes. We used an inferred bedrock lowering rate estimated by Reneau and Dietrich (1991) in the Oregon Coast Range to roughly approximate a sediment input rate to the channels we investigated. We used the maximum bedrock lowering rate ($1{\cdot}1 \times 10^{-4}$ m a^{-1}), which was inferred from the volume of colluvium stored in dated bedrock hollows (Reneau and Dietrich, 1991) and a soil to bedrock bulk density ratio of 0·5 (Reneau and Dietrich, 1991; Heimsath *et al*., 2001). The maximum bedrock lowering rate was selected because it was in close agreement with the catchment-averaged erosion rate of $1{\cdot}2 \times 10^{-4}$ m a^{-1} estimated by Heimsath *et al*. (2001) in this area. Basin area of the erosional zone was multiplied by the lowering rate, and adjusted for the change in density. The underlying assumption of using this method for predicting input to the channel is that sediment production and delivery are in equilibrium. This method for predicting sediment input is a rough approximation; however, it provides a reasonable estimate in the absence of a feasible method to directly calculate sediment input to the channels we investigated.

RESULTS

Dendrochronology

Because debris flows typically remove all vegetation in the valley bottoms (Costa, 1984), dendrochronology was an adequate measure of the time since the previous debris flow. Even-age cohorts of trees lined the valley floors, and these linear patches of vegetation were younger than trees on the surrounding hillslopes. Age estimates of the 13 debris flow runout paths ranged from 4 to 144 years since the previous debris flow (Table II). In order to estimate the lag time between debris flow occurrence and tree establishment, two debris flows with a known time of occurrence were compared with the age of tree cores sampled from the erosional zone. Bear T11 (Figure 1) had an even age cohort of alders that ranged from 18 to 20 years of age. No debris flow was detected in this tributary on 1972 aerial photographs; however, a debris flow runout path was observed on 1979 aerial photographs. A large storm event in November–December 1975 triggered numerous landslides and debris flows in the area (Swanson and Swanson, 1977). If the debris flow in Bear T11 was associated with the 1975 storm, there was a lag time of up to 5 years in the tree ring record. A debris flow in Cedar Creek, also in the Siuslaw River drainage, also had a known time of occurrence in 1975 (Swanson and Swanson, 1977). The age of alder trees in the erosional zone ranged from 18 to 22 years, indicating a lag time of 3 to 7 years for tree establishment.

No trees were growing in the erosional zone of two of the channels in our study basins. The debris flow in Bear T13 was known to have occurred during a large storm event in 1996. No trees had become established in the erosional zone in the 4 years since this debris flow; however, young alder seedlings had rapidly recolonized the deposit. Skate T6 was heavily shaded and also had no trees present in the erosional zone, and this channel had extremely low volumes of wood and sediment. A landslide near the channel head was visible on air photos from 1968; therefore, it was assumed that this debris flow occurred during an extremely large storm in 1964.

Table II. Particle size of streambed surface layer and average length of bedrock reaches

Time since debris flow (years)	Tree species	Tributary	Percent channel area by substrate size					Average length of bedrock reaches (m)
			Fines	Gravel	Cobble	Boulder	Bedrock	
4	–	BT13	1	7	3	3	86	57
20	Red Alder	BT11	4	24	7	2	62	22
36	–	ST6	0	6	4	0	89	85
84	Red Alder	ST5	4	20	11	13	52	32
88	Hemlock	BT12	3	23	11	5	58	17
114	Hemlock	BT5	11	29	14	22	24	11
121	Douglas Fir	ST4	2	35	14	11	36	13
123	Douglas Fir	ST3	3	28	11	14	45	28
124	Douglas Fir	BT9	5	39	18	19	20	9
127	Douglas Fir	BT4	7	38	12	12	32	14
129	W. Red Cedar	BT3	14	35	12	17	21	7
143	W. Red Cedar	ST8	3	45	12	9	30	9
144	Douglas Fir	BT7	10	35	20	22	13	9

Trees established since the previous stand-replacement fire on mid- and upper-elevation hillslopes were younger than trees growing on the low-elevation valley floors. All trees sampled on mid- and upper hillslopes were <148 years of age. The average age of tree cores from these slope positions was 133 ± 11 years ($\pm$ one standard deviation), and the average diameter was 85 ± 23 cm ($\pm$ one standard deviation). The maximum tree ring count from the low-elevation valley floors of Skate and Bear Creeks was 315 years, the average was 251 ± 54 years ($\pm$ one standard deviation), and the average diameter was 163 ± 30 cm ($\pm$ one standard deviation). The age of tree cores extracted from the extremely large trees growing on the low-elevation valley floor surfaces are only a partial age based on the number of tree rings counted. Only the outer 46 cm of these large diameter trees could be extracted, and the centre of the tree could not be sampled; therefore, the reported age underestimates the actual age.

Accumulation rates

The estimated time since the previous debris flow was used to calculate accumulation rates for sediment and wood. An exponential model was the best fit to the wood volume and age data (Figure 2). Accumulation rates of wood ranged from 0·003 to 0·03 $m^3\ m^{-1}\ a^{-1}$. Time since the last debris flow accounted for 70 per cent of the observed variance in wood volume ($p < 0{\cdot}01$). Sediment also accumulated at a non-constant rate, and a power function explained 88 per cent of the observed variance ($p < 0{\cdot}01$; Figure 3). The exponent in a power function relationship represents the constant of proportional change (Church and Mark, 1980) in the ratio of y (sediment volume) to x (time). If the exponent is equal to one the ratio is constant; however, the exponent in this case was $>1{\cdot}0$ (lower 95 per cent confidence interval = 1·13; upper 95 per cent confidence interval = 1·85). An exponent greater than one indicates that sediment volume increased out of proportion to time. Lower accumulation rates were observed immediately following a debris flow, whereas higher accumulation rates were observed as the time since the previous debris flow increased. This pattern suggests that the ability of the channel to retain sediment increased disproportionately through time. The volume of in-stream wood was strongly associated with the volume of sediment in the channel, and sediment storage increased linearly in proportion to the volume of in-stream wood (Figure 4).

From the chronosequence approach a temporal succession of changes in channel morphology can be perceived for the erosional zones of past debris flows (Figure 5). Immediately following a debris flow the channel was predominantly bedrock, with almost no sediment or wood in storage. During the first 50 years following a debris flow, small discrete patches of sediment were stored behind individual logs, but the channel was predominantly bedrock. One hundred years after a debris flow almost half of the channel length was still exposed bedrock (Figure 6). By 144 years, the maximum age of channels we investigated, discrete patches of sediment coalesced to form larger, more continuous patches. Beyond this point in time, the channel would be

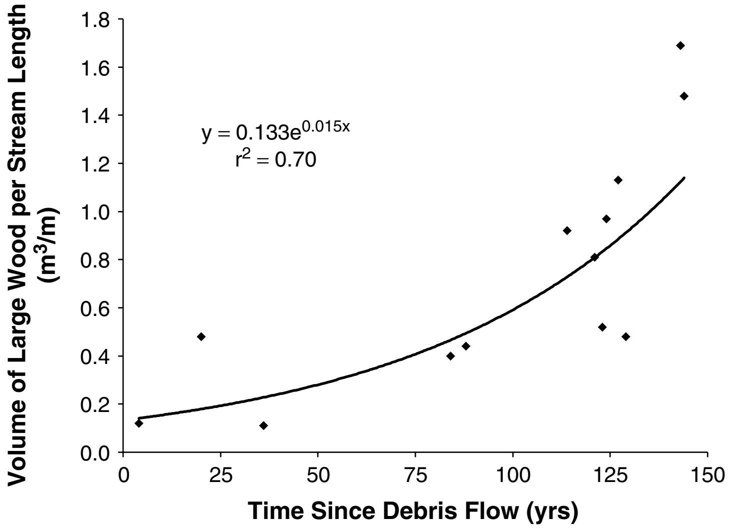

Figure 2. Volume of large wood in the study streams based on the time since the previous debris flow as estimated by dendrochronology

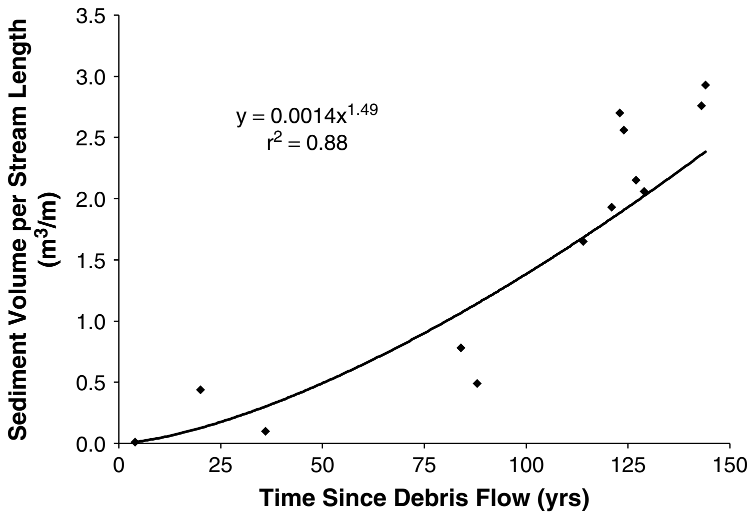

Figure 3. Sediment accumulation in the study streams based on the time since the previous debris flow as estimated by dendrochronology

predicted to have an almost continuous covered of sediment, with very little exposed bedrock. The decrease in the proportion of the channel with exposed bedrock, and the average length of bedrock reaches with increased age, depicts how these discontinuous patches of sediment coalesced through time (Table II).

Landslides from bedrock hollows and on planar sideslopes appeared to be an important source of sediment to the channels we investigated. Unfortunately, it was not possible to quantify the long-term contribution of sediment delivered from landslides because landslide scars were rapidly vegetated, and only failures that occurred in the last decade could be detected. Where landslide scars could be detected, the scar was measured, and this volume accounted for an average of 19 per cent of the sediment stored in the channels.

The observed volume of sediment stored in the channel was contrasted with a predicted input rate (Table III; Figure 7) calculated from the maximum bedrock lowering rate ($1{\cdot}1 \times 10^{-4}$ m a^{-1}) and a soil to bedrock bulk density ratio of 0·5 estimated by Reneau and Dietrich (1991). The observed volume of sediment stored in the

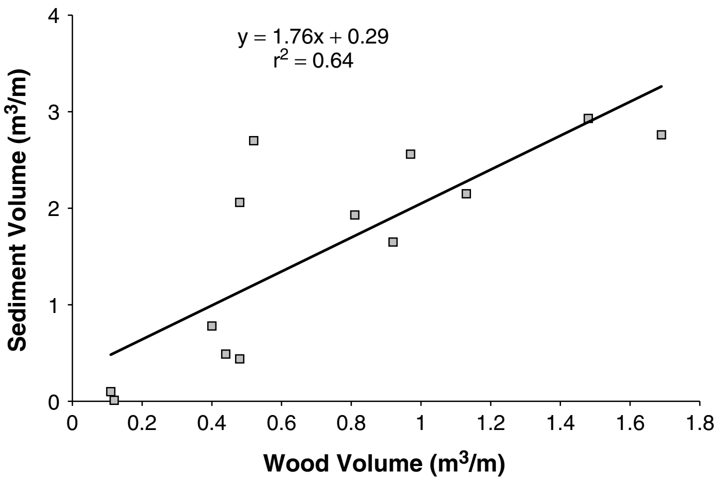

Figure 4. The association between wood and sediment storage volumes in debris-flow-prone channels

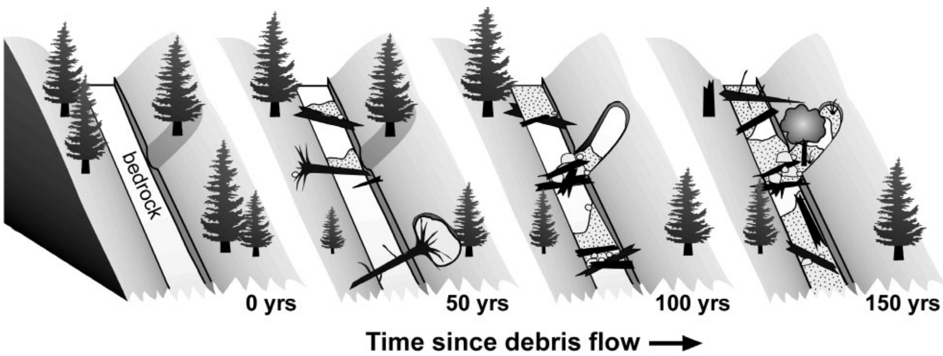

Figure 5. Conceptual illustration of the changes in channel morphology based on the time since the previous debris flow

channel was less than predicted from the bedrock lowering rate. The area between the curves can be used for a rough approximation of the amount of sediment exported by fluvial transport. Immediately following a debris flow the majority of sediment entering the channel is likely to be transported downstream. As the time since the previous debris flow increases, the proportion of sediment exported appears to decrease.

Basin-scale sediment storage

The quantity of sediment stored in debris flow runout paths was contrasted with the volume of sediment stored in the mainstem channel and valley floor landforms of Skate Creek. Wood provided a physical obstruction to sediment transport, and 73 per cent of the sediment in tributaries that are prone to debris flows was stored directly behind wood (Figure 8). Large wood stored 59 per cent of this sediment, and small wood (pieces <2 m in length and <20 cm average diameter) stored 14 per cent. A total of 389 pieces of wood was measured in debris-flow-prone tributaries to Skate Creek, and 37 per cent of these pieces stored sediment. Wood >15 m in length accounted for only 22 per cent of the number of pieces, but accounted for 78 per cent of the total volume of wood. Despite this inconsistency, the number of pieces explained 60 per cent (r^2) of the observed variance in the volume of wood in the channels.

Large wood was also a major component of sediment storage in the mainstem of Skate Creek (Figure 8); however, <0·5 per cent of the sediment in the mainstem was stored by small wood. In contrast to the

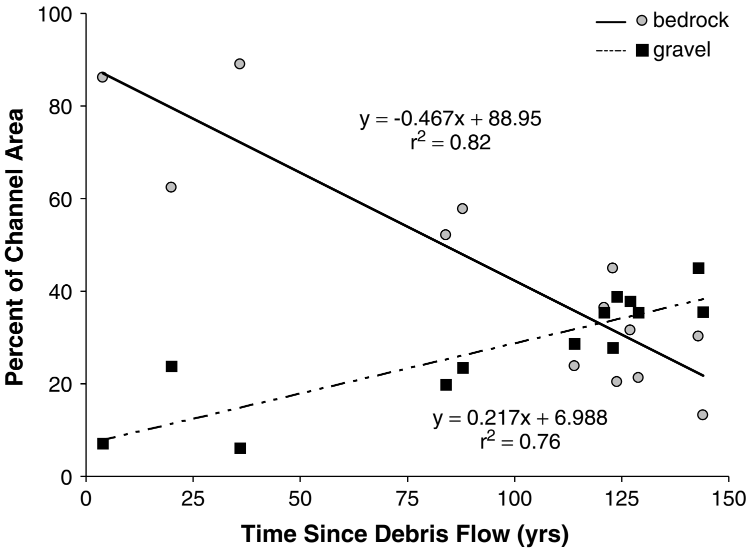

Figure 6. Changes in the proportion of the channel length with exposed bedrock and gravel, based on the time since the previous debris flow

Table III. Measured sediment storage volumes and predicted sediment input volumes estimated from a long-term average bedrock lowering rate (Reneau and Dietrich, 1991)

Tributary	Time since debris flow (years)	Erosional zone sediment volume (m^3)	Sediment volume predicted from bedrock lowering (m^3)
Skate T3	123	939	1005
Skate T4	121	1110	1012
Skate T5	84	223	503
Skate T6	36	27	180
Skate T8	143	800	947
Bear T3	129	443	443
Bear T4	127	546	582
Bear T5	114	394	529
Bear T7	144	1138	737
Bear T9	124	1183	611
Bear T11	20	106	165
Bear T12	88	208	544
Bear T13	4	27	44

tributaries, the mainstem had low-gradient reaches (1–5 per cent slope) where sediment was stored in the absence of wood or boulders.

Wood influenced channel morphology on multiple spatial scales. Individual pieces, or small accumulations of wood, functioned to store sediment at small spatial scales (10^0–10^1 m). These individual pieces were relatively abundant and broadly distributed spatially throughout the channel network. In contrast, large, valley-spanning wood dams formed by debris flows stored sediment on larger spatial scales (10^1–10^2 m) and inundated entire stream reaches and valley floor surfaces. These large dams were infrequent and were discretely located near tributary junctions. Two large, valley-spanning wood dams formed by debris flows in the last 30 years were located in the mainstem of Skate Creek. These debris flows originated in the upper portion of the basin where timber was harvested in the mid-1970s. The channel was actively incising the wedge of

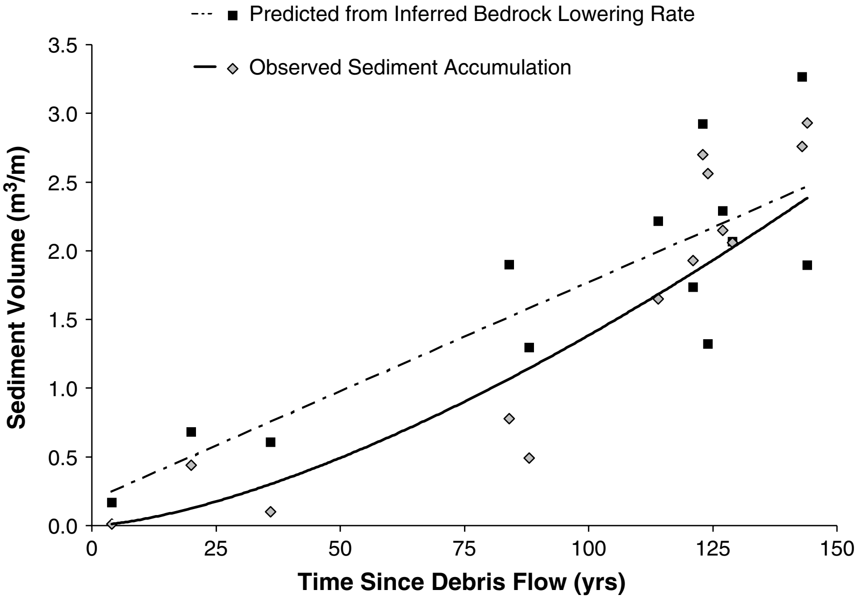

Figure 7. Measured sediment accumulation compared to a predicted sediment input volume from an inferred bedrock lowering rate (Reneau and Dietrich, 1991). The observed sediment accumulation rate was based on field measurements from our study streams, solid line regression equation $y = 0{\cdot}0014x^{1{\cdot}49}$, $r^2 = 0{\cdot}88$. Predicted sediment input from an inferred bedrock lowering rate was $1{\cdot}1 \times 10^{-4}$ m a^{-1} multiplied by the drainage area and a soil to bulk density ratio of 0·5, dashed line regression equation $y = 0{\cdot}016x + 0{\cdot}168$, $r^2 = 0{\cdot}70$. The area between the curves represents the proportion of sediment presumably exported by fluvial transport

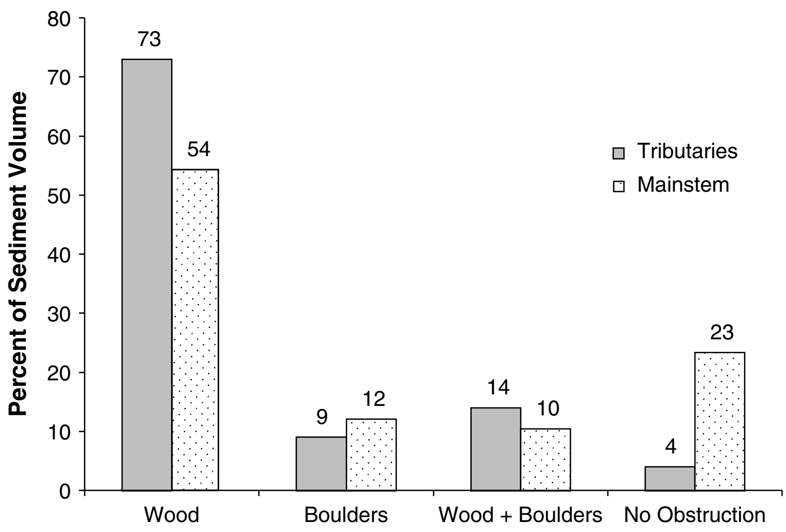

Figure 8. Sediment stored by obstructions in the channel network of Skate Creek. Numbers represent the percentage of stored sediment

sediment upstream of the debris dam, resulting in the formation of continuous terraces along the channel. These large dams stored 32 per cent of the sediment in the mainstem, and individual pieces of wood and small accumulations accounted for 22 per cent.

A total channel length of 6860 m was surveyed in Skate Creek, and a total volume of 21 950 m^3 of sediment in storage was estimated in this portion of the channel network. Numerous first-order channels throughout the network were not investigated; therefore, the proportion of the network in low-order colluvial channels was substantially under-represented. The majority of sediment in the network was stored in tributaries (Figure 9),

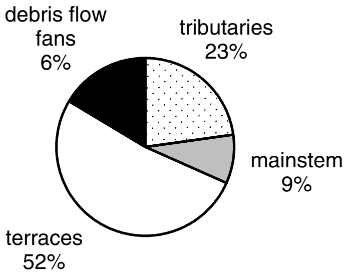

Figure 9. The proportion of sediment stored in the channel network and valley floor landforms of Stake Creek

which also constituted 69 per cent of the channel length investigated. The third-order mainstem of Skate Creek was 2100 m long, had an average channel gradient of 6 per cent, an average valley floor width of 18 m, and an average bank-full channel width of 5 m. The mainstem channel stored a relatively small proportion of sediment and had an average depth of alluvium of <40 cm.

In addition to the channel network, 47 560 m^3 of sediment were stored in valley floor landforms along the mainstem of Skate Creek. Terraces contained the majority of the sediment in storage; however, remnant debris flow fans also contained a substantial volume of sediment (Figure 9). These valley floor landforms along the mainstem stored 2·2 times more sediment than the entire channel network; however, the residence time for this sediment is typically longer than sediment stored in the channel network (Dietrich and Dunne, 1978). The total volume of sediment in the channel and valley floor was equivalent to 491 years of annual soil production based on a bedrock lowering rate of $1{\cdot}1 \times 10^{-4}$ m a^{-1} and a soil to bedrock bulk density ratio of 0·5 (Reneau and Dietrich, 1991).

DISCUSSION

Sediment dynamics

The approach of using a space-for-time substitution provided a means for examining stream channel structure over longer time scales than direct observation would permit. The underlying assumption of the space-for-time approach is that individual channels were similar except for the time since disturbance. This assumption is only reasonable when other site factors have a minimal effect on the observed patterns. We attempted to investigate channels with similar characteristics by constraining the portion of the channel network we examined to high-gradient, second-order streams in close proximity to each other. Drainage area and channel gradient were not significant variables for predicting the volume of sediment in the channel when compared with the age data in a multiple linear regression model ($p > 0{\cdot}1$). This result supports the assumption that the time since the previous debris flow was the primary mechanism behind the observed pattern.

The approach to estimating sediment and wood accumulation rates also had underlying assumptions. The first assumption was that previous debris flows evacuated all sediment and wood from the erosional zone. There is no direct evidence that the channels we investigated were completely scoured to bedrock; however, field observations from a previous study of 53 debris flows triggered during a large regional storm event in 1996 in this area indicated that incomplete evacuation of material stored in high-gradient channels was uncommon (May, 2002). Benda and Cundy (1990) also documented that channels with slopes >20 per cent were consistently scoured to bedrock by debris flows in almost all streams investigated. The second assumption was that dates derived from tree cores were a reasonable estimate of the actual time since the last debris flow. The lag time in tree establishment appears to be relatively short (3–7 years); however, there is no information available on a potential lag-time among species related to successional patterns.

For nearly a century after a channel is scoured by a debris flow, the majority of the channel length is still predominantly bedrock. There is no evidence to suggest that bedrock channels persist for this length of time because of a limited supply of sediment. Our data suggest that these channels are limited by the storage capacity of the channel. Exposed bedrock is an important consideration in the long-term development of the channel because the accumulation of sediment can protect the underlying bedrock from erosion during the interval between debris flows and therefore limit the rate of incision. Bedrock channels also provide a very high energy and simplistic form of habitat for the numerous amphibians and invertebrates that reside in these small streams. Because the proportion of exposed bedrock was highly correlated with the time since debris flow, it can also be used to approximate the disturbance history in surveys of other channels (May, 2001).

The observed volume of sediment and wood in channels was highly correlated with the time since the last debris flow. The non-linear pattern of sediment accumulation suggests that immediately following a debris flow the sediment transport capacity of the channel is relatively high, and the storage capacity is low. Field evidence suggests that debris flows cause an extended pulse of secondary erosion by undercutting the base of the adjacent hillslopes. This pulse of sediment input is not reflected in the sediment accumulation data because bedrock channels in this portion of the network have a high transport potential and may lack the ability to store sediment in the absence of large obstructions.

Large wood was the focal point for sediment accumulation because it provided a physical obstruction to sediment transport. Sediment accumulation increased linearly in proportion to the volume of wood in the channel. As wood accumulation in the channel increased through time, the storage capacity of the channel also increased and a series of positive feedbacks could be initiated. Sediment that was stored behind wood in the channel increased the streambed roughness, decreased the local slope of the channel, and reduced the capacity for sediment transport. As a greater proportion of the streambed was covered by sediment, roughness continued to increase and more of the water could begin to flow subsurface, further decreasing surface water velocities. In addition, vegetation became established and root networks held the sediment in place. Dietrich and Dunne (1978) documented a similar pattern of non-linear sediment accumulation for bedrock hollows that were infilling by local diffusion.

The short-term pattern of sediment accumulation we observed was lower than the estimated input rate predicted by a long-term average bedrock lowering rate (Reneau and Dietrich, 1991). A rough estimate of the volume of sediment lost to fluvial export can be estimated from the area between the curves in Figure 7. This pattern suggests that the proportion of sediment lost to fluvial export decreased through time because the channel became more retentive. Analysis of the volume of sediment stored annually compared to the predicted sediment input rate suggests that sediment storage exceeded the proportion of sediment exported by fluvial transport approximately 60 years after a debris flow. Swanson *et al.* (1982) deduced that low-order streams might be aggrading on a time scale of years and decades, while experiencing net degradation on a longer time scale. The long-term history of degradation is apparent in the incised topography of these steep-sided, V-notch valleys.

Wood dynamics

Currently, there is little information on how the abundance of in-stream wood is linked to landscape processes that typically have temporal cycles of activity of decades to centuries. A confounding problem is that field measurements are commonly taken at a single point in time in highly variable systems that are strongly influenced by stochastic processes. Bilby and Ward (1989) observed that the frequency of wood pieces decreased as stream size increased. Examination of their data also revealed that the absolute variability in the abundance of wood increased as stream size decreased (R. E. Bilby, personal communication, 2001). A high degree of variability in wood abundance was also observed in the low-order streams we investigated; however, the time since the last debris flow explained 57 per cent of the variance. Our results suggest that wood abundance increased in a predictable way following a stochastically driven disturbance.

Large wood can play a vital role in channel morphology in mountainous terrain because it provides the cornerstone for sediment accumulation in channels that would otherwise be bedrock dominated (Montgomery *et al.*, 1996). Bilby and Ward (1989) suggested that small streams cannot transport large wood by chronic fluvial processes, and therefore, recruitment processes in the adjacent hillslopes and riparian areas determine the spatial distribution of wood in the channel. In higher-order streams, the distribution of large wood depends both on local recruitment and upstream sources. During the interval between debris flows, low-order streams had the potential to store an abundance of wood delivered from the local hillslopes. As individual sediment accumulations coalesced and sediment depth increased, wood that had previously fallen into the channel became buried. Wood that was buried could decay more slowly and therefore have a longer residence time in the channel (Hyatt and Naiman, 2001).

A relatively small proportion of wood pieces (37 per cent) were actively storing sediment, and small pieces of wood were more frequently associated with sediment storage as stream size decreased. Similarly, Bilby and Ward (1989) observed that nearly 40 per cent of pieces of wood in channels less than 7 m wide were associated with sediment accumulations, and the proportion of pieces storing sediment decreased as channel width increased.

Debris flow occurrence

The occurrence of debris flows in relation to forest fires is an issue of great concern in steep, mountainous terrain. Several researchers have proposed that large-scale, severe fires are associated with pulses of debris flow activity (Swanson, 1981; Meyer *et al*., 1992; Benda and Dunne, 1997). Charcoal in sediment from Little Lake in the Oregon Coast Range suggests that under the climate conditions of the past 9000 years, the mean fire interval in this area has been 230 years (Long *et al*., 1998). Alternatively, a dendrochronology-based study that directly overlapped the Little Lake basin suggested that the natural fire rotation for large-scale, stand-replacement fires was 452 years during the pre-settlement period (Impara, 1997). The low-elevation valley floors of Skate and Bear Creeks had not experienced a stand-replacement fire for >315 years. Tree ring data from mid- and upper elevations of the basins suggest that the time since the previous stand-replacement fire was approximately 148 years. A fire reconstruction study located only 10 km north of our study basins documented a large-scale, high severity wildfire in 1852 (Impara, 1997). Although this fire was recorded as the fire episode of 1852 in the dendrochronology record (Impara, 1997), local historical records documented a fire event in 1849 that reportedly burned >2000 km^2 (Morris, 1934).

Our study indicates that a pulse of debris flow activity occurred following the last stand-replacement fire on mid- and upper-slope positions. During the 30 years following the 1849 fire event, 54 per cent of the tributaries we investigated experienced a debris flow (Figure 10). The average background rate of debris flow activity was 1·5 debris flows (12 per cent of the channels investigated) per 30-year period, and debris flow activity increased by 42 per cent above the background rate in the immediate post-fire time period. Swanson (1981) suggested that fire-induced accelerated erosion may persist for 20 to 30 years in western Oregon. Although 30 years appears to be an extended time period for fire effects to be manifested, our age dates may be underestimated by up to 10 years. Furthermore, results of this study are a conservative estimate of post-fire debris flow occurrence because recent debris flows would have erased any evidence of earlier, post-fire debris flows if they had occurred. Based on the background rate of debris flow activity that we observed, evidence for the post-fire debris flow signal would continually decrease as time since the previous fire increased.

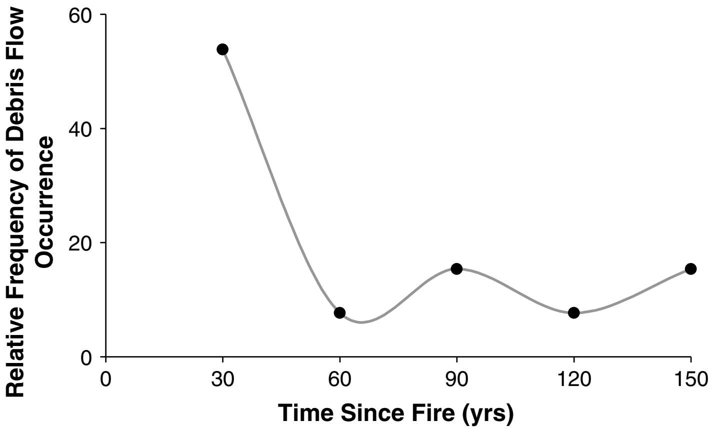

Figure 10. Debris flow activity in the immediate post-fire and inter-fire time periods in Skate and Bear Creeks. Data are grouped into 30 year age classes and the trend line was added to illustrate the overall pattern

Past fires did not burn homogenously in the study basins. In mid- and upper elevations, where landslides initiate debris flows, fires may burn more frequently than on low-elevation valley floors. Impara (1997) observed a similar pattern of greater fire frequency on mid- and upper-hillslope positions compared to low-elevation valley floors, and fire occurrence was not influenced by aspect. Although the most recent fire in the upper slopes of our study basins did not directly impact the low elevation channels and valley floors (i.e. the fish-bearing portion of the channel network), the disturbance was propagated through the network by debris flows in the tributaries.

In addition to post-fire debris flow activity, a substantial background rate of debris flow activity was observed. In the absence of a recent fire or timber harvest activities, high-intensity rainstorms triggered debris flows in 46 per cent of the second-order channels we investigated. Older forests may be susceptible to landsliding when gaps in the forest create areas of relatively low root cohesion (Schmidt *et al.*, 2001). This result has important implications for sediment routing because it indicates that sediment inputs to downstream channels are distributed more evenly through time than a fire-based disturbance model would predict (Benda and Dunne, 1997). The potential for debris flow deposits to influence in-stream habitat may be a function of the age of the deposit (Hogan*et al.*, 1998). The asynchronous timing of debris flows in the inter-fire period may create a greater variety of deposit ages, and therefore a higher diversity in the structure and function of deposits.

The average background rate of debris flows was 0·04 debris flows per year. Based on the mean fire interval of 452 years reported in the study area by Impara (1997), an estimate of 18 debris flows would be expected to occur between fire events in the study basins. At this frequency debris flow activity in the inter-fire time period would exceed debris flow activity observed in the immediate post-fire time period. High-intensity rainstorms occur more frequently than fires in this region, therefore, fires may not be the dominant influence on long-term rates of debris flow activity in this area.

The average rate of debris flow occurrence in the study basins was 0·018 km^{-2} a^{-1}. This annual probability of debris flow occurrence was similar to the value reported by Swanson *et al.* (1982) in the Cascade Range of Oregon (0·017 km^{-2} a^{-1}). These rates of debris flow occurrence were within the range of long-term landslide rates observed in bedrock hollows in the Oregon Coast Range (0·01 to 0·03 km^{-2} a^{-1}; Montgomery *et al.*, 2000).

Implications for forest management

Low-order streams drain the majority of the land-base in mountainous terrain and can be very sensitive to erosional processes such as landslides; however, very little research has been focused on this portion of the network. Results of this study provide insights into a temporal succession of channel morphology following disturbance, and the sediment retention capacity of debris-flow-prone channels. Wood supplied from the streamside forests played a critical role in the development of channel structure in this portion of the network.

Small streams in forested basins are often the most directly impacted by land-use activities (Beschta and Platts, 1986); however, policy and management historically placed less emphasis on these small, often ephemeral, tributary channels and their associated riparian habitats. Bedrock channels in basins intensively managed for timber production may be more abundant and more persistent than in unlogged forests. If landslide-prone hillslopes are logged, there may be an increase in landslide and debris flow activity (Montgomery *et al.*, 2000; May, 2002). This increase in debris flow frequency would transition a greater proportion of low-order streams into a bedrock state. Concurrently, if low-order basins are managed for intensive timber harvest on a short rotation age or if no streamside buffers are retained, recruitment of wood to the channel can be diminished. If these low-order streams are depleted of present or future sources of wood, the sediment storage capacity of the basin may be drastically reduced. Without the input of wood, channels that have been transformed into a bedrock state may persist in this state for a prolonged period of time. Because there is no sediment storage in bedrock channels, these channels become an efficient conveyor of sediment delivered from the hillslopes. This would represent a major shift in processes, with low-order channels becoming a chronic source of sediment to downstream areas instead of an episodic source.

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