Steven A. Acker[1], Olympic National Park, 600 East Park Avenue, Port Angeles, Washington 98362,

Timothy J. Beechie, National Oceanic and Atmospheric Administration, Northwest Fisheries Science Center, 2725 Montlake Boulevard East, Seattle, Washington 98112

and

Patrick B. Shafroth, U.S. Geological Survey, Fort Collins Science Center, 2150 Centre Avenue, Building C, Fort Collins, Colorado 80526

Effects of a Natural Dam-Break Flood on Geomorphology and Vegetation on the Elwha River, Washington, U.S.A.

Abstract

Ephemeral dams caused by landslides have been observed around the world, yet little is known about the effects of their failure on landforms and vegetation. In 1967, a landslide-dam-break flood in a pristine reach of the Elwha River valley filled the former channel and diverted the river. The reach is a reference site for restoration following the planned removal of dams on the river. We identified five surfaces on the 25 ha debris fan deposited by the flood. Based on tree ages and historic air photos, three of the surfaces formed in 1967, while two formed later. The surfaces varied in substrate (silt and sand, to boulders), and height above the river channel. Tree mortality resulted from tree removal and burial by sediment, the latter leaving snags and some surviving trees. Tree species composition was generally consistent within each surface. Dominant species included red alder (*Alnus rubra*) and Sitka willow (*Salix sitchensis*), alone or in combination, a combination of Douglas-fir (*Pseudotsuga menziesii*) and black cottonwood (*Populus balsamifera* ssp. *trichocarpa*), or a combination of alder and cottonwood. There were significant differences between surfaces in stem density, basal area, and rate of basal area growth. The large degree of heterogeneity in forest structure, composition, and productivity within a relatively small floodplain feature is in part due to spatial variability in the intensity of a single disturbance event, and in part due to the occurrence of subsequent, smaller events. To recreate natural diversity of riparian forests may require mimicking the variety of physical and biotic habitats that a single, complex disturbance event may create.

Introduction

The biological diversity and productivity of unmanaged riparian forests are maintained by the interplay between fluvial and successional forces. Fluvial processes build and destroy surfaces, creating a complex patchwork of sites varying in resource availability and flooding regime. Plants of various species undergo recruitment, growth, and death in response to these gradients, and influence fluvial processes by stabilizing banks, trapping sediment, and modifying flows (Gregory et al. 1991, Naiman et al. 1993, 1998, Hughes 1997, Latterell et al. 2006, Montgomery and Abbe 2006).

Fluvial processes include landslide delivery of sediment and wood to channels (Benda et al. 1998), transport of sediment and wood (Johnson et al. 2000, O'Connor et al. 2003), lateral migration of channels (Beechie et al. 2006), channel narrowing (Scott et al. 1996), and floodplain erosion and aggradation (Hughes 1997), all of which promote a shifting mosaic of river and floodplain habitats (Ward and Stanford 1983). The significance of large but rare events such as landslides also varies among and within watersheds. Landslides that block river channels, the most extreme example of sediment delivery to rivers, have occurred repeatedly in many areas of the world (Costa and Schuster 1988, Korup 2002). Several landslide dams have been documented in the mountainous portions of the Pacific Northwest of the U.S., including the Olympic Peninsula (Schuster et al. 1992, 2000, O'Connor 2004).

Persistence of landslide dams varies from minutes to millennia, though half fail within 10 days and persistence for more than one year is relatively rare (Costa and Schuster 1988, Korup 2002). When landslide dams fail, instantaneous flows often exceed recorded floods, and the flood waters may carry sediment from many locations within the landslide deposit (Costa and Schuster 1988, Korup 2002). Due in part to the ephemeral nature of most landslide dams, and to the improbability of witnessing a failure, there have been few studies of the geomorphic consequences of

[1] Author to whom correspondence should be addressed.
E-mail: steve_acker@nps.gov

failure of landslide dams (Korup 2002). Studies of the ecological consequences of the failure of landslide dams are even rarer.

We examine the influence of a recent landslide dam-break flood on floodplain forests in a pristine valley of the Elwha River on the Olympic Peninsula in the Coastal Forest ecoregion of the Pacific Northwest, USA. We first characterize the geomorphic surfaces and sediment texture of the disturbance generated by a 1967 dam-break flood described by Tabor (1987) and at least two subsequent events. We then document the response of the vegetation to these disturbances in terms of tree mortality, tree species composition, vegetation structure, and tree growth rates. We conclude by considering how the varied disturbance processes within and between discrete events have generated existing composition and structure of woody vegetation.

The study site is within an area considered to be a "reference ecosystem" for restoration efforts to follow planned dam removals in the Elwha watershed (Clewell et al. 2000, Society for Ecological Restoration International Science & Policy Working Group 2004, Duda et al. 2008). With respect to vegetation, one of the central objectives of the dam removal project is to "restore the ecosystem to a close approximation of the conditions and processes found prior to dam construction…" (DOI 1996:452). The landslide-dam-break we studied was a natural process and so is relevant to restoration objectives. However, we do not suggest that the failure of a natural landslide dam is a useful analogue for the planned removal of the constructed dams. Rather, we assert that understanding natural disturbance regimes and mechanisms is critical to effective vegetation restoration. In the context of reference ecosystems, another objective of our study was to ascertain whether conceptual models developed from study of nearby rivers on the west side of the Olympic Peninsula might help explain the complexity of landforms and vegetation along the Elwha River.

Study Area

The 72 km-long Elwha River flows northward out of the Olympic Mountains to the Strait of Juan de Fuca on Washington State's Olympic Peninsula (Figure 1), draining an area of approximately 830 km^2 (see Duda et al. 2008 for more information on climate and hydrology of the watershed). Geyser Valley, an unregulated alluvial reach upstream of the upper dam between rkm 28 and rkm 32, may be the best model of pre-dam geomorphology for the area inundated by the upper dam on the Elwha River (Gilbert and Link 1995, DOI 1996). However, floodplain morphology and disturbance regimes are undocumented and there is little information upon which to base a strategy for restoration of floodplain forests. One of the most significant events to occur

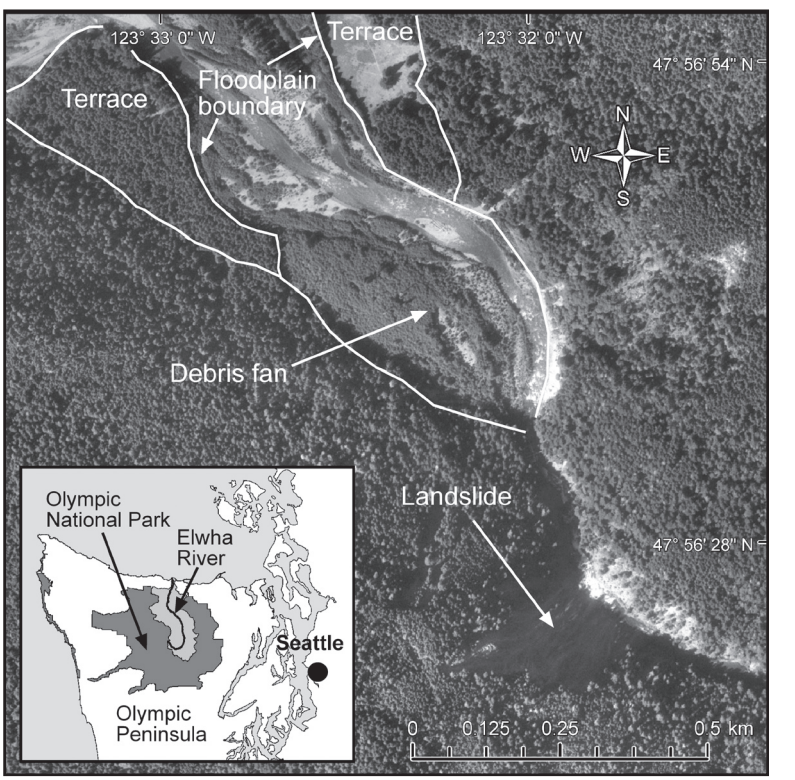

Figure 1. Geyser Valley aerial photograph (2002) showing locations of (1) landslide that likely triggered dam-break flood of 1967, (2) location of dam-break flood deposits, and (3) boundaries of the contemporary floodplain and terraces. Inset shows location of the Elwha River on the Olympic Peninsula in Washington State, USA.

in the Elwha River in recent decades was the failure of a natural landslide dam just upstream of Geyser Valley in the Grand Canyon of the Elwha. The 1967 landslide briefly dammed the Grand Canyon and then failed (Tabor 1987), releasing a flood wave several meters high and depositing sediments in a 25 ha debris fan that extended over 500 m downstream. Approximately 18 ha of the fan have been recolonized by a mosaic of riparian forest patches. Subsequent dam-break floods continue to modify fan surfaces and vegetation patterns.

Methods

Mapping and Description of Geomorphic Surfaces

We characterized geomorphic surfaces in the study area using a combination of elevation and grain size transects, as well as field mapping of surface boundaries on aerial photographs. We surveyed three transects across the debris fan and one profile down the longitudinal axis using a laser range finder (Laser Technology, Inc., Impulse LR200) and stadia rod. Survey points included all major breaks in topography or changes in dominant particle sizes of surface sediments. At each point we recorded the surface elevation and described the range of particle sizes within a 1 m diameter circle centered on the survey point. The dominant particle size at each point was visually estimated in the field as sand or finer (< 2 mm diameter), gravel (2-64 mm), cobble (64-256 mm) or boulder (> 256 mm). We also mapped boundaries between depositional surfaces, which reflected either (1) zones of contrasting energy of flow within the initial dam-break flood of 1967, or (2) subsequent events that eroded portions of the 1967 surface and overlaid new deposits. In the field we identified boundaries between surfaces as locations of either abrupt changes in slope, abrupt changes in surface texture, or both. On aerial photography most boundaries were identifiable by changes in vegetation type or age, which facilitated mapping of boundaries for later transfer to a geographic information system (GIS). Mapping of boundaries by global positioning system was not feasible in this steep-walled valley.

Mapping Channel and Vegetation Patches Through Time

In order to determine the time course of changes in the river channel and vegetation patches, we examined aerial photographs taken before and after the 1967 dam-break flood. The only photograph taken prior to the dam-break flood was in 1939, and post-flood photographs were available for the years 1968, 1976, 1981, 1990, and 2000. Original photograph scales ranged from approximately 1:12,000 to approximately 1:24,000. Photographs were scanned and orthorectified in order to track vegetation disturbance and establishment at specific points in time. The poor resolution of the earliest photos prevented detailed analysis of vegetation types, but we were able to recognize four cover classes in all years: stream channel (the wetted channel and any gravel bars within its boundaries), unvegetated floodplain surfaces, forest that was established prior to the 1967 flood, and forest that became established after the 1967 flood. The map of geomorphic surfaces was digitized from the field map and superimposed on the images from each year. We then overlaid a grid of points spaced 15 m apart, recorded the cover class at each point in each year, and summarized proportions of cover classes within the boundaries of each surface in each year. Several points along the floodplain boundary could not be evaluated consistently between years because the adjacent high terrace shaded the edge of the floodplain in some years. These points were excluded from the analysis. A total of 528 points were evaluated, with the number per surface ranging from 29 to 214.

Description and Aging of Stands on Present-Day Surfaces

We measured tree ages and composition and structure of woody vegetation on the surfaces identified by the geomorphology surveys, using three to five, 0.025 ha, circular plots per surface. Plot locations were selected randomly from a grid of points that was generated in GIS and overlaid on the map of geomorphic surfaces. Plot centers were constrained so that the entire plot would be on one surface, and so that the nearest plot center would be at least two plot diameters away.

In each plot, we recorded the species and measured the diameter at breast height (dbh, 1.37 m) of every tree 5 cm dbh and larger. For standing snags and uprooted trees, we recorded species, dbh, and decay class. Using the system of Maser et al. (1988), the least-decayed snags or logs (i.e., fine twigs present) were classified as decay class 1, the most-decayed (i.e., extensive rot in heartwood) were classified as decay class 5, and pieces

intermediate in decay were classified as classes 2 through 4 depending on amounts of branch, bark, and bole decay. Because we recorded few live trees ≥ 35 cm dbh, we considered all snags larger than 35 cm dbh to be remnants of the stand existing prior to the 1967 dam-break flood. Within each plot, we recorded the presence of woody understory species, which we defined as woody plants not large enough to be measured as trees (i.e., < 5 cm dbh). Woody understory included seedlings or small saplings of tree species. Nomenclature follows Hitchcock and Cronquist (1976).

To determine minimum surface age and tree growth rates, we extracted increment cores from the largest trees on each plot. We aged 97 trees, from six species: grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl.), red alder (*Alnus rubra* Bong.), black cottonwood (*Populus balsamifera* ssp. *trichocarpa* [Torr. & Gray ex Hook.] Brayshaw), Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco), Sitka willow (*Salix sitchensis* Sanson ex Bong.), and *Tsuga heterophylla* [Raf.] Sarg.). All are shade intolerant, except for grand fir and western hemlock, which account for five of the 97 trees (Minore 1979, DeBell 1990, USDA, NRCS 2005); thus, ages should approximate the date of past disturbances. For species with at least 10 individuals in the plot, we cored the three largest trees. If any of the three largest trees in a plot were of less common species, we also cored those trees. For trees 15 cm dbh or larger, we obtained two cores per tree, separated by at least 90 degrees. We obtained one core for trees less than 15 cm dbh. Cores were extracted as close to the ground surface as possible and exact core heights were recorded. In the laboratory, we mounted and sanded the cores, and counted annual rings under a microscope. To convert from age at core height to total tree age, we used published values of species-specific height-growth rates (King 1966, Wiley 1978, DeBell 1990, Foiles et al. 1990, Harrington et al. 1994). Lacking published information for Sitka willow, we assumed that its early height growth was equivalent to that of red alder. Only two of the cored trees were older than the 1967 dam-break flood, both grand firs about 120 years in age. These two trees were excluded from calculations of surface age and tree growth rates.

Using tree age and diameter data, we calculated rates of basal area growth, and scaled up the values from trees to plots to geomorphic surfaces. We compared stand structure and tree growth rates between surfaces using ANOVA with Tukey's Studentized Range Test for comparison of means (SAS Institute Incorporated 1989). We used $P \leq 0.05$ to assess significance of all statistical tests.

Results

Disturbance History and Geomorphic Surfaces

Prior to the dam-break flood of 1967 the Elwha River flowed in a straight channel through the study reach, bordered by mature forest on both banks and aligned with the canyon upstream (Figure 2). In the year after the dam-break flood (1968), the flood deposit evidently filled the straight channel and forced the main channel more than 100 meters to the east. The forest on the floodplain to the west of the channel remained standing, but most trees appeared dead. By 1976, the channel had moved farther to the east, exposing a new surface deposited at the eastern edge of the 1967 flood deposits. The channel continued to erode eastward into the terrace of glacial sediments after 1976 and by 1981 had deposited a second new surface to the east of the 1967 flood deposits. By the year 2000, the study site attained the configuration mapped during this study.

Our survey identified five major surfaces within the fan area, excluding the contemporary gravel bars of the Elwha River (Figure 3). Based on ages of the vegetation plots (Figure 4), all surfaces post-date the 1967 dam-break flood. Surfaces 3a, 3b, and 4 date approximately to the 1967 dam-break flood, with first tree establishment no later than 1971, 1970, and 1969, respectively (Table 1). The coarse boulders of surface 3a indicate a region of high energy flow oriented along the fan's long axis, and in approximate alignment with the canyon immediately upstream. There was little fine-grained sediment within this deposit, forming a substrate of large boulders with large interstitial spaces. The peak elevation of the surface was approximately 4 m above the present day river bed, or more than 2 m above contemporary bankfull floods (Figures 3 and 5). Surface 3b surrounded the upstream portion of the boulder field, and consisted of boulders within a matrix of finer gravels and sand. The elevation of surface 3b was 1 to 2 m lower than the main boulder field at transect A-A′, or 2 to 3 m above the present-day river bed. Partially vegetated overflow channels that are

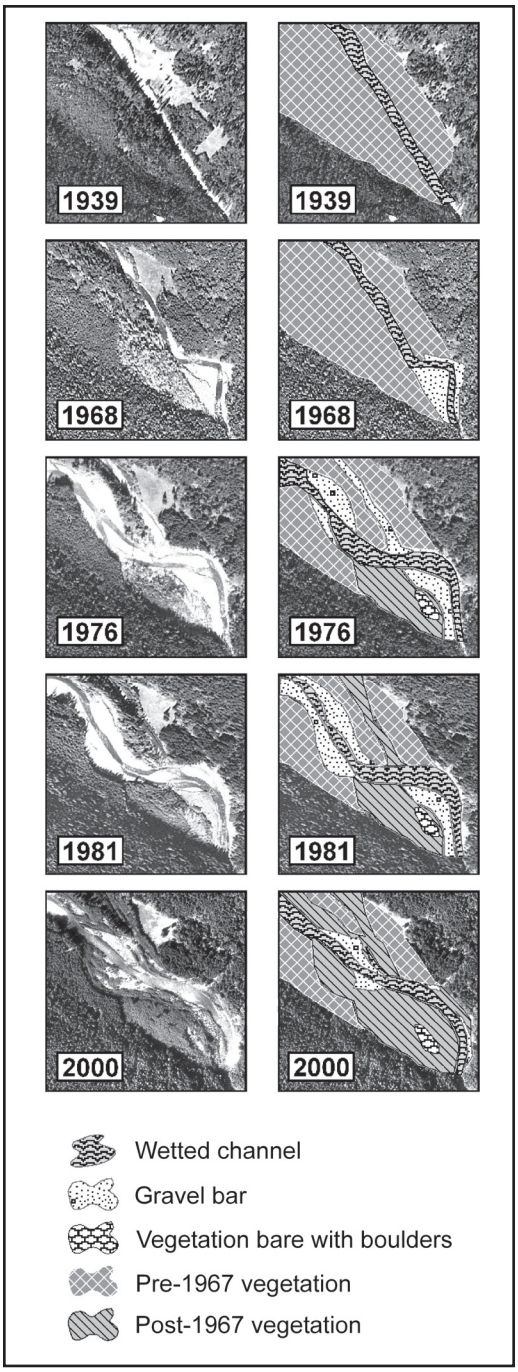

Figure 2. Aerial photograph time series of the study site illustrating straight channel prior to the dam break flood (1939), channel shift eastwards after the dam-break flood (1967), and subsequent vegetation and channel changes. The non-forested patch in the center of the upper edge of each photograph is a persistent meadow on a terrace.

etched into surface 3b on both sides of the boulder field indicate that flood flows scour this surface at infrequent intervals. At the downstream end of the boulder field (transect B-B′), surfaces 2, 3a, and 3b have roughly equal maximum elevations and all are approximately 1m higher than surface 4. Surface 4 is the distal portion of the fan, characterized by silt and sand overlying cobbles and boulders. Much of the surface is near the elevation of the present-day river bed. Coarser sediments beneath the layer of fines are most likely deposits of the 1967 dam-break flood, and finer grained deposits on the surface are probably attributable to post-1967 floods.

Surfaces 1 and 2 evidently post-date the 1967 event, with deposits overlying eroded portions of surfaces 3b and 4. Surface 2 dates to a depositional event between 1976 and 1977, and surface 1 dates to an event between 1981 and 1984 (Table 1). The tree establishment year for one plot on surface 2 was the same as that of plots on surface 1 (Figure 4), indicating either that trees established later on some portions of surface 2 or that we were unable to correctly identify the boundary between the two surfaces in the field. Surface textures of the two surfaces were similar, and the boundary between them indistinct. However, most of surface 2 was higher than surface 1, and an eroded edge of surface 2 (near transect C-C′) and a remnant boulder berm (near transect B-B′) suggest that the two surfaces were from different depositional events. Examination of eroded edges of these deposits indicated no stratification, sorting, or imbrication to a depth of at least 1 m. The deposit contained little clay or silt, suggesting rapid bed-load deposition during hyperconcentrated flow (a depositional environment intermediate between normal stream flow and debris flow [Pierson and Costa 1987]).

Vegetation Response

Tree mortality occurred due to a variety of disturbance events and processes on the five surfaces. The 1967 dam-break flood removed some trees on all surfaces, converting mature conifer forest to river channel (Figure 6). The intensity of disturbance ranged from removal of 100% of the pre-1967 forest in the area that is now surface 2, to removal of < 1% in the area of surface 4. On surfaces 3b and 4, the major effect of the 1967 dam-break flood was evidently partial burial by fine sediments, with most of the forest left standing.

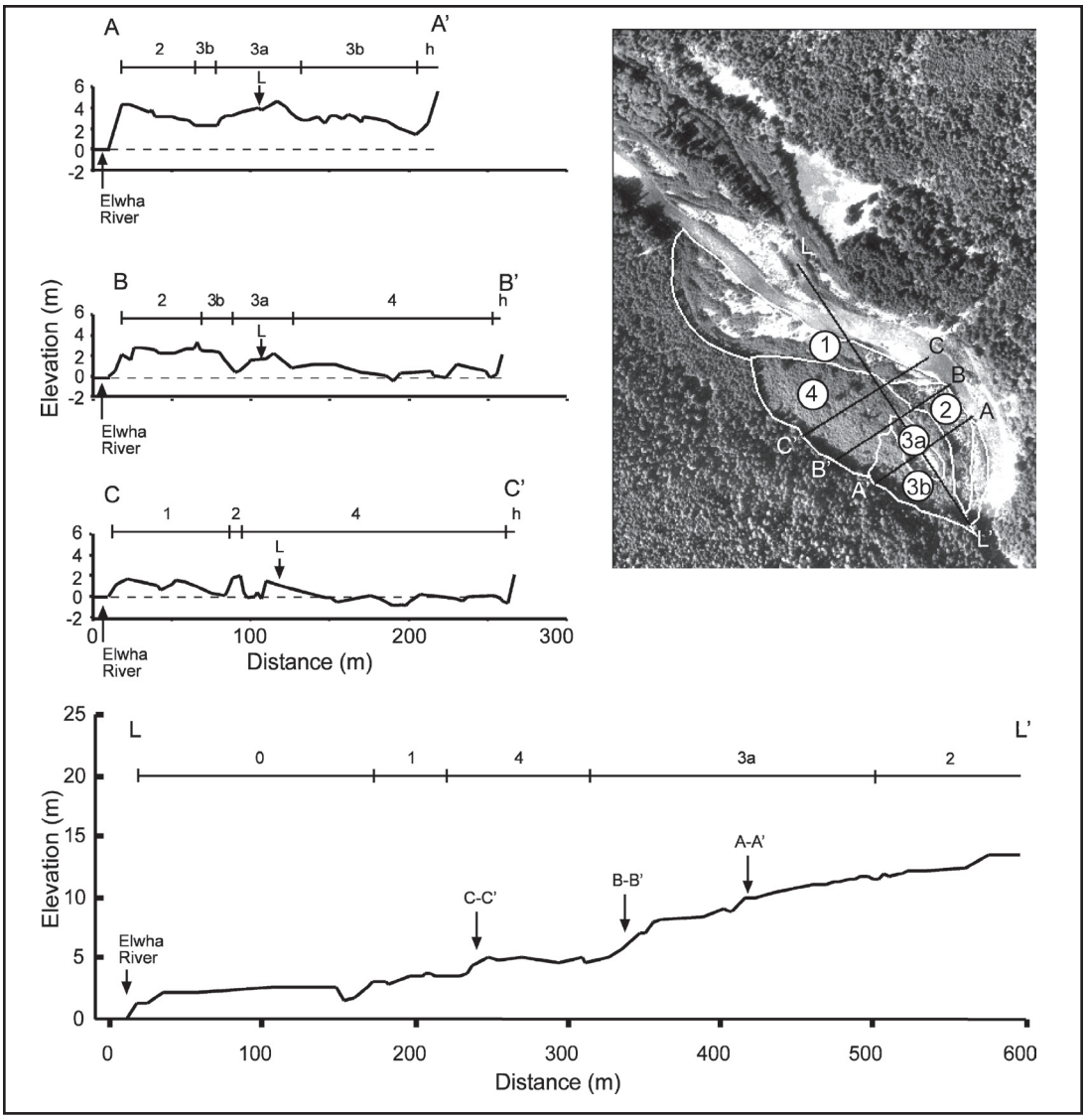

Figure 3. Cross sections (A-A′, B-B′, C-C′) and longitudinal profile (L-L′) of dam-break flood deposits located at the upstream end of Geyser Valley, Elwha River, Washington. Line above each profile illustrates locations of geomorphic surfaces. Surface 0 is the contemporary gravel bar. Surface 1 is the most recent dam-break flood deposit (dating to 1984). Surface 2 is an intermediate age dam-break flood deposit (dating to 1977). Surfaces 3a, 3b, and 4 are from the 1967 dam-break flood. Transect locations are shown on aerial photograph at upper right.

Nearly all trees on these two surfaces were dead by 1976. Snags ≥ 35 cm dbh, apparent remnants, occurred on three of five plots on these two surfaces and nowhere else. Nearly all of the snags were conifers, and most were well decayed (≥ class 3). The mean snag density on surface 3b was 80 per ha (38 SE); on surface 4 the mean density was 64 per ha (29 SE). An event after the 1967 flood, between 1968 and 1976, removed more of the earlier forest from surface 1 than did the 1967 flood (Figure 6).

Trees began to establish on all surfaces one to four years after surface creation (Table 1). There has been a prolonged period of tree recruitment, especially on surfaces 3b and 2 (Figure 4). Present day tree species composition was generally

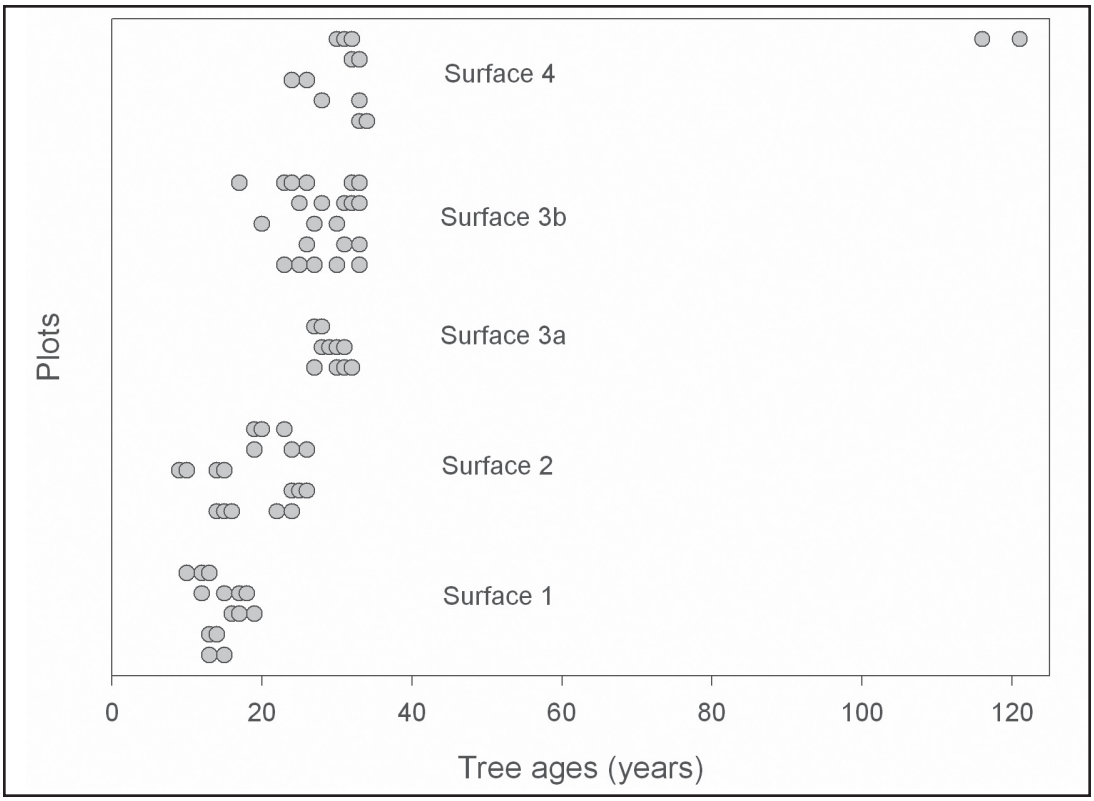

Figure 4. Ages of trees within plots, grouped by geomorphic surface. Each horizontal line of points represents one plot.

TABLE 1. Maximum tree ages on geomorphic surfaces, first year of tree establishment (based on tree cores), and range of years in which the surface may have been deposited. Earliest year of deposition based on aerial photograph sequence; latest year based on first year of tree establishment.

Surface	Maximum tree age on surface[1]	First year of tree establishment	Year of surface deposition
1	19	1984	1981-1984
2	26	1977	1976-1977
3a	32	1971	1967-1971
3b	33	1970	1967-1970
4	34	1969	1967-1969

[1]Excluding two grand firs >100 years old on surface 4. See methods for additional explanation.

consistent among plots within each of the five surfaces; there were also similarities between some of the surfaces (Figures 7 and 8). Surface 4 was characterized by red alder and surface 1 by either Sitka willow or alder, or a mixture of both.

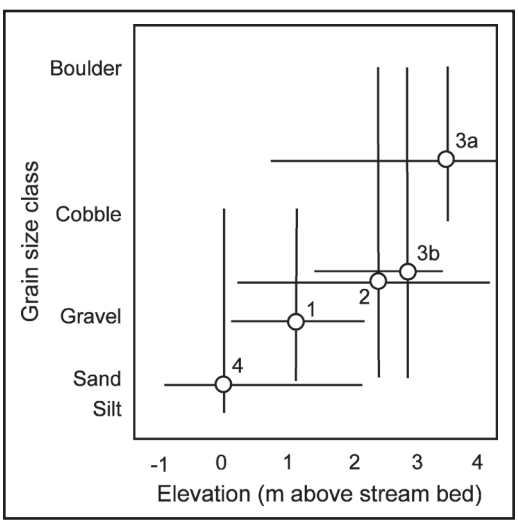

Figure 5. Elevation and grain size ranges of the five geomorphic surfaces. Points indicate median grain size class and median elevation of surface above the present stream bed measured along transects, and lines indicate the range of elevation and grain size classes of each surface.

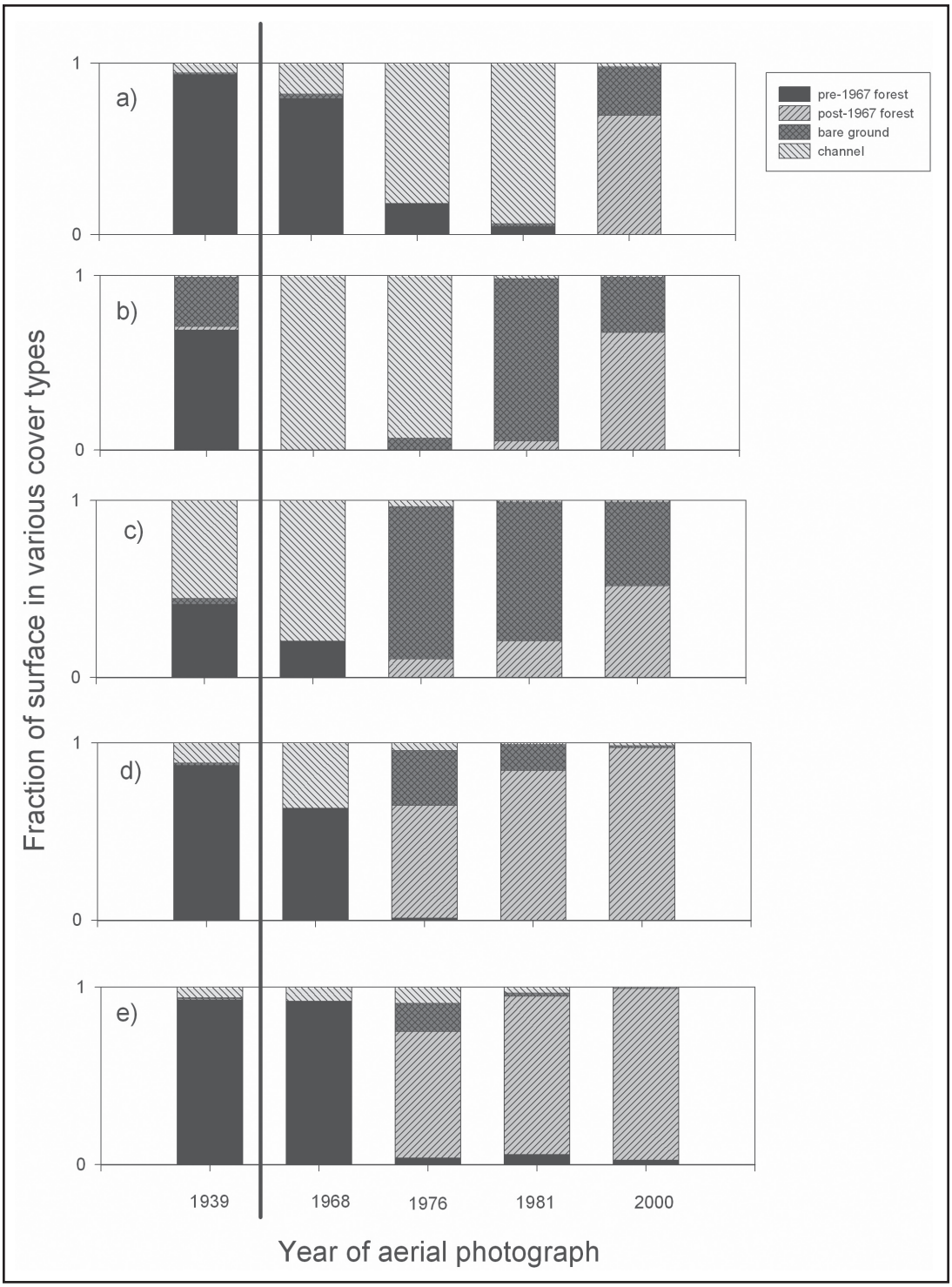

Figure 6. Proportions of area in different cover types on the geomorphic surfaces derived from the aerial photograph time series of the study site: a) surface 1; b) surface 2; c) surface 3a; d) surface 3b; e) surface 4.

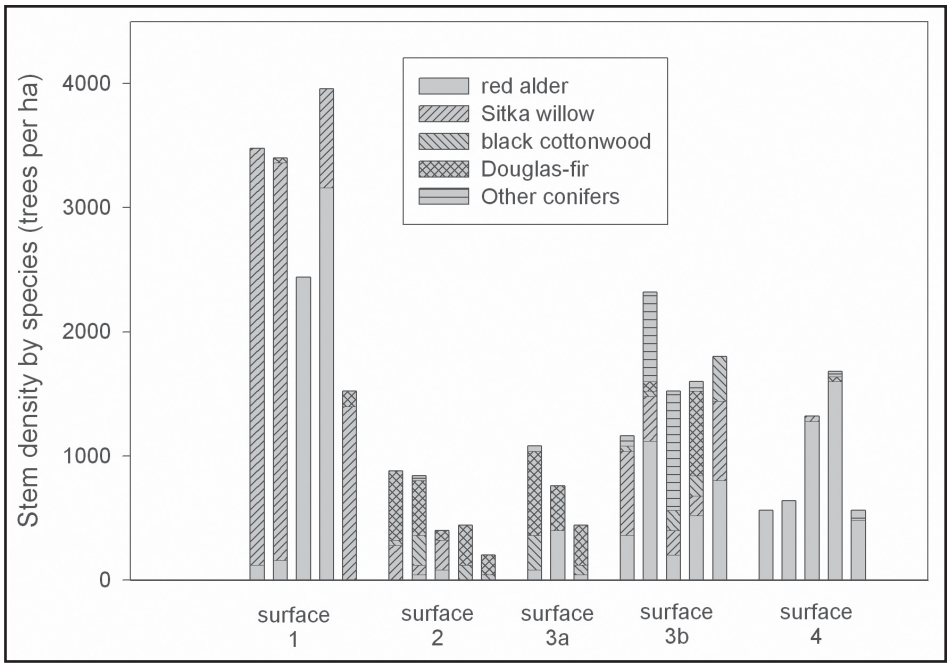

Figure 7. Stem density (numbers of trees per ha) by species for plots on the five geomorphic surfaces. Bars represent the replicate plots on each surface.

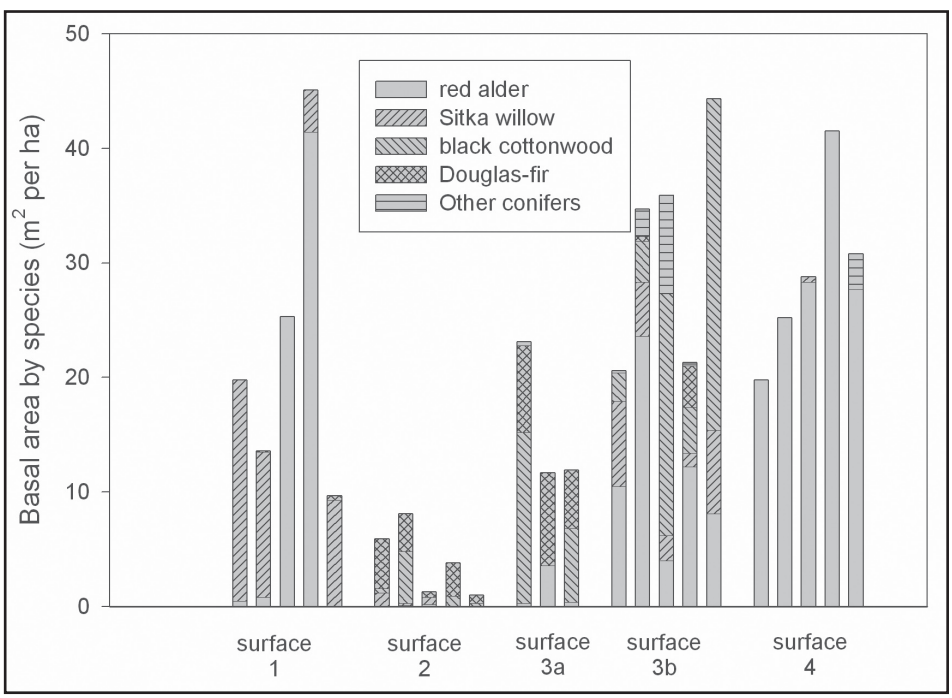

Figure 8. Basal area of trees (m^2 per ha) by species for plots on the five geomorphic surfaces. Bars represent the replicate plots on each surface.

TABLE 2. Woody understory species (tree regeneration and shrubs) occurring with a frequency of at least 50% by geomorphic surface.

Surface	Species
1	red alder, Sitka willow
2	grand fir, red alder, western white pine (*Pinus monticola* Dougl.), black cottonwood, Douglas-fir, Sitka willow
3a	grand fir, big-leaf maple (*Acer macrophyllum* Pursh), Douglas-fir
3b	grand fir, ocean-spray (*Holodiscus discolor* (Pursh) Maxim.), stink currant, swamp gooseberry, salmonberry, Pacific blackberry (*Rubus ursinus* Cham. & Schlecht.), western red cedar (*Thuja plicata* Donn), western hemlock
4	swamp gooseberry, blackcap (*Rubus leucodermis* Dougl.), salmonberry

Surfaces 2 and 3a were dominated by Douglas-fir and black cottonwood, with willow abundant on surface 2 and alder abundant on surface 3a. Surface 3b was dominated by alder and cottonwood, though willow, Douglas-fir, and other conifer species are also abundant.

The woody understory consisted of 17 species of shrubs, six species of conifer seedlings and small saplings, and four species of hardwood tree seedlings and small saplings. Seven of the species occurred on only one plot, while 15 species had a frequency of at least 50% in plots on at least one surface. With respect to these common species, the surfaces split into two groups (Table 2). The woody understory of surfaces 1, 2, and 3a was characterized by regeneration of mostly shade-intolerant tree species (Minore 1979). By contrast, most of the common woody understory species on surfaces 3b and 4 were shrubs, including several characteristic of moist habitats (Pojar and MacKinnon 1994): stink currant (*Ribes bracteosum* Dougl. ex Hook.); swamp gooseberry (*Ribes lacustre* [Pers.] Poir.), and salmonberry (*Rubus spectabilis* Pursh). Several shade-tolerant tree species were also common in the understory on surface 3b (Minore 1979).

There were consistent differences among the surfaces with respect to stand structure, whether measured by stem density, basal area, mean dbh, or maximum dbh (Table 3). Both basal area and stem density varied by almost an order of magnitude, whereas mean and maximum dbh varied by about a factor of two. Surface 1 was characterized by numerous, small trees; surface 4 had fewer, larger trees; and surface 3b was intermediate between surfaces 1 and 4 in tree density and size. Surface 2 stood out because of its relatively few, small trees. Surface 3a had trees of similar size to surface 3b, but they were fewer in number. With respect to basal area, values were lowest on surface 2, while differences among the other surfaces were not statistically significant (Table 3).

Based on ANOVA for both entire plots and individual cored trees, surfaces were significantly different with respect to basal area growth ($P = 0.0015$ and $P = 0.0023$, respectively). Plot-level basal area growth was highest on surfaces 1, 3b, and 4, and lowest on surface 2 (Table 4). The only statistically significant difference in basal area growth of individual cored trees was between surface 2 (low growth) and surfaces 4 and 3b (high growth; Table 4).

TABLE 3. Forest structure (standard error) on the five geomorphic surfaces created by a landslide-dam-break flood on the Elwha River. *F* and *P* are values for ANOVA (d.f. = 4,18 in all cases) and means followed by the same letter are not significantly different.

	Stem Density (ha^{-1})	Mean dbh (cm)	Maximum dbh (cm)	Basal Area (m^2/ha)
Surface 1	2960^{a} (436)	$9^{c,d}$ (1)	$19^{b,c}$ (3)	22.7^{a} (6.2)
Surface 2	552^{c} (132)	9^{d} (1)	16^{c} (2)	4.0^{b} (1.4)
Surface 3a	$760^{b,c}$ (185)	15^{b} (1)	35^{a} (5)	$15.6^{a,b}$ (3.8)
Surface 3b	1688^{b} (197)	$13^{b,c}$ (1)	$39^{a,b}$ (4)	31.3^{a} (4.6)
Surface 4	$920^{b,c}$ (207)	20^{a} (2)	$33^{a,b}$ (4)	29.2^{a} (3.6)
F	13.9	23.6	9.0	6.9
P	<0.0001	<0.0001	0.0004	0.0015

TABLE 4. Basal area growth rates (standard error) on the five geomorphic surfaces based on both entire plots, and individual cored trees. *F* and *P* are values for ANOVA (d.f. = 4,18 in all cases) and means followed by the same letter are not significantly different.

	Plot-level Basal Area Growth Rate (m^2/ha/yr)	Tree-level Basal Area Growth Rate (cm^2/yr)
Surface 1	1.38 [a] (0.68)	14.8 [a,b] (1.9)
Surface 2	0.17 [c] (0.11)	6.3 [c] (0.9)
Surface 3a	0.51 [b,c] (0.19)	16.2 [a,b] (3.8)
Surface 3b	0.97 [a,b] (0.33)	19.2 [a] (3.8)
Surface 4	0.92 [a,b] (0.27)	24.1 [a] (2.6)
F	6.9	4.6
P	0.0015	0.0023

Discussion

Physical Processes of Disturbance and Surface Development

The patterns and processes we observed on the Elwha River correspond in many ways to the models developed for rivers on the west side of the Olympic Peninsula. Our study area is similar to a "patchwork floodplain" as defined by Montgomery and Abbe (2006: 153). That is, it has been formed "by coalescence of local depositional features with up to several meters of relief on the surface of the active valley bottom…" Lateral channel migration played a key role in creating the complexity of landforms and vegetation we observed, much as Latterell et al. (2006) and O'Connor et al. (2003) observed. The landslide and subsequent dam-break flood are examples of high sediment supply and "active bedload transport… of tectonically active regions" that Montgomery and Abbe (2006: 154) cite as required for development of patchwork floodplains. Moreover, the sediment accumulation left by the dam-break flood forced the Elwha against the valley wall, further increasing input of sediment and wood into the river as O'Connor et al. (2003) describe.

The most significant difference between our observations and the models for the nearby rivers is the lack of large wood. All three of the recent studies of rivers on the west side of the Olympic Peninsula indicate that the fundamental process of floodplain creation is the accumulation of stable logjams around "key pieces," i.e., "pieces of wood large enough to remain stable during bed mobilizing flows and trap other floating wood" (Latterell et al. 2006:536) and sediment (O'Connor et al. 2003, Montgomery and Abbe 2006). Stable logjams can provide appropriate germination conditions for riparian plant species (e.g., fine sediments, organic matter) and reduce shear stress and inundation, leading to additional sediment deposition and surfaces up to several meters above the active channel (Fetherston et al. 1995). Eventually, these surfaces are colonized by conifers which can grow large enough to serve as key pieces, completing the cycle of landform creation and destruction mediated by large wood (O'Connor et al. 2003, Latterell et al. 2006, Montgomery and Abbe 2006).

The surfaces we observed were created by deposition of sediments in the 1967 dam-break flood and subsequent events, rather than by logjams. The interaction of flow and sediment with little or no involvement of large wood resulted in channel migration and formation of new surfaces. Although many of the conditions for wood-mediated fluvial processes apply to our study area, these were superseded by the geomorphic context of our study site. The site is within an unconstrained, montane reach, and the surrounding vegetation includes numerous large trees of species with decay-resistant wood. However, it is immediately downstream of the transition from a long, highly-constrained, steep-sided reach which is vulnerable to landslides. Thus, our study site occupies a location where large wood in the channel is likely to be minimal (Rot et al. 2000), but sediment is likely to be abundant. It is possible that elsewhere along unconstrained reaches of the Elwha River large wood plays the role described for rivers on the west side of the Olympic Peninsula.

Forest Heterogeneity and Productivity

The high heterogeneity in forest structure, composition, and productivity within the relatively small floodplain feature we studied is due in part to spatial variability in the intensity of a single disturbance event, and in part to the occurrence of subsequent, smaller events. Spatial variation in intensity of the 1967 dam-break flood created three surfaces (3a, 3b, and 4) which contrast markedly in surface texture and height above the river channel. The 1967 flood also varied spatially in the proportion of trees removed versus trees partially buried in fine sediment, resulting in presence or

absence of snags and residual trees. The forest stands that have developed are all approximately the same age and vary by a factor of two with respect to stem density, basal area, and basal area growth rate. Species composition ranges from a mixture of Douglas-fir and black cottonwood to nearly pure red alder. The sparsely stocked, less-productive stand of Douglas-fir and cottonwood occurs on the higher, coarser-textured surface left by the 1967 flood.

Subsequent events added two surfaces (1 and 2) that were intermediate between the extremes of the surfaces created by the 1967 flood in terms of surface texture and height above the river. However, the forest stands on the surfaces were quite dissimilar: one was dominated by Douglas-fir and black cottonwood, and had the lowest stem density, basal area, and basal area growth rate of all the surfaces; the other was dominated by red alder and Sitka willow and had the highest stem density and basal area growth rates of all the surfaces. These differences appear to be due to lower soil moisture on the surface dominated by Douglas-fir and cottonwood, due in turn to greater elevation above the river (up to 4 m). The commonness of drought-tolerant Douglas-fir (Minore 1979) in the understory is consistent with relatively dry conditions.

The heterogeneity in forest structure and composition we observed has several implications for riparian-aquatic interactions. The variation in species composition between surfaces contributes to the maintenance of structure and function of aquatic habitats because species such as Douglas-fir and black cottonwood grow large enough to serve as anchoring pieces of wood in instream jams (Collins and Montgomery 2002) and fast-growing, smaller hardwoods such as red alder contribute material that accumulates in jams (Collins and Montgomery 2002, Balian and Naiman 2005). In addition, on the surfaces where they occur, snags and residual trees are likely to promote continued recruitment of conifers (especially shade-tolerant species) in the floodplain, as availability of coarse woody debris is the most important limitation on riparian conifer establishment where seed rain is sufficient (Beach and Halpern 2001).

The two surfaces with abundant Douglas-fir (surfaces 2 and 3a) also had the lowest density of trees of any of the surfaces. Nierenberg and Hibbs (2000) found that floodplain areas with few or widely-spaced trees were common in the Oregon Coast Range. The most likely explanations revolve around salmonberry, either preventing initial tree regeneration due to competition, or colonization of the understory of post-disturbance red alder stands by salmonberry which subsequently suppresses tree regeneration after death of alder—typically at 100 years or less (Harrington et al. 1994, Nierenberg and Hibbs 2000). Neither of these apply to our case, given the lack of salmonberry and the young age of the surfaces. For the older of the two sparsely-stocked surfaces, nearly half of the area is still open after about 30 years (Figure 6); it may continue to have low tree cover due to the boulder substrate. The concept of an 'edaphic gap,' i.e., "canopy openings which are associated with an identifiable edaphic or topographic condition, such as a streamcourse or thin soils on a rock outcrop" (Lertzman et al. 1996: 1256), appears to be a better explanation of vegetation structure for this surface than processes associated with shrub competition. Van Pelt et al. (2006) have also described a similar situation for the Queets River. The highest areas resulting from channel avulsion and incision may lack fine sediment and have low soil moisture. Van Pelt et al. (2006) term such areas "dry cobblefields" and report that woody plant regeneration is sparse to absent on such sites.

There is little published information on structure and productivity of unmanaged, young riparian forest in the Pacific Northwest, with two recent exceptions. Two separate studies on the Queets River reported similar values to ours for stem density of surfaces 18 to 41 years old (Balian and Naiman 2005), and for stem density and mean dbh for surfaces 22 to 39 years old (Van Pelt et al. 2006). Basal area values were similar to our observations, with the exception that none of the values reported from the Queets approached the low basal area on surface 2. Basal area growth was almost 40% higher than the highest value we observed (1.9 m^2/ha/yr) for the one study on the Queets River which measured productivity (Balian and Naiman 2005). The western lowlands of the Olympic Peninsula, such as the Queets valley, are known for highly productive forests (Henderson et al. 1989). The strong climatic gradients on the peninsula, especially decreasing precipitation from southwest where the Queets is located to northeast where the Elwha is located (see Figure 2 in Duda et al. 2008), explain much of the difference between our sites and the Queets studies.

Implications for Restoration

Natural, catastrophic disturbances are an important source of the diversity of riparian forests. Diversity is generated both by the presence of patches of varying ages since disturbance, and heterogeneous substrates and biological legacies created within individual disturbance events. Disturbance effects can vary in the time required to become manifest, for example from the minutes it may take for a channel avulsion to remove trees, to the years it may take for the death of mature trees partially buried in fine sediment. Restoration of riparian forests, such as following removal of dams on the Elwha River, should be planned with such events in mind. To recreate natural diversity of riparian forests may require mimicking the variety of physical and biotic habitats that a single, complex disturbance event may create. In addition, the potential for such events to occur during the course of restoration should be assessed. Areas with large accumulations of coarse sediments, such as the deltas at the upstream ends of the reservoirs (DOI 1996), may spawn disturbances similar to the landslide-dam-break flood. The benefits of extensive plantings in such areas should be weighed against the potential for removal or burial of plants by sediment-laden flood waters. Use of knowledge from other river-floodplain systems to develop reference conditions for ecological restoration must take into account the differences in natural regimes of flow, sediment, and wood that underlie differences between even nearby rivers in floodplain processes and patterns (O'Connor et al. 2003).

Acknowledgements

We thank Roger Hoffman for GIS support, including selection of locations for vegetation sampling. For assistance with fieldwork, we thank Matt Albright, Bill Baccus, John Boetsch, Michele Laubenheimer, Wendy McClure, Roger Hoffman, and Leigh Winowiecki. We thank Kris Kloehn for the analysis of aerial photographs. We greatly benefited from reviews of an earlier version of the manuscript provided by Rebecca Brown, Jonathan Friedman, Scott Stolnack, Steven M. Wondzell, and an anonymous reviewer. The use of trade, firm, or corporation names in this publication is for the convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Government of any product or service to the exclusion of others that may be suitable.

Literature Cited

Balian, E. V. and R. J. Naiman. 2005. Abundance and production of riparian trees in the lowland floodplain of the Queets River, Washington. Ecosystems 8:841-861.

Beach, E. W. and C. B. Halpern. 2001. Controls on conifer regeneration in managed riparian forests: effects of seed source, substrate, and vegetation. Canadian Journal of Forest Research 31:471-482.

Beechie, T. J., M. Liermann, M. M. Pollock, S. Baker, and J. Davies. 2006. Channel pattern and river-floodplain dynamics in forested mountain river systems. Geomorphology 78:124-141.

Benda, L. E., D. J. Miller, T. Dunne, G. H. Reeves, and J. K. Agee. 1998. Dynamic landscape systems. *In* R. J. Naiman and R. E. Bilby (editors), River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer, New York. Pp. 261-288.

Clewell, A., J. Rieger, and J. Munro. 2000. Guidelines for developing and managing ecological restoration projects. Society for Ecological Restoration, Tucson, AZ.

Collins, B. D. and D. R. Montgomery. 2002. Forest development, wood jams, and restoration of floodplain rivers in the Puget Lowland, Washington. Restoration Ecology 10:237-247.

Costa, J. E. and R. L. Schuster. 1988. The formation and failure of natural dams. Geological Society of America Bulletin 100:1054-1068.

DeBell, D. S. 1990. *Populus trichocarpa* Torr. & Gray black cottonwood. *In* R. M. Burns and B. H. Honkala (technical coordinators), Silvics of North America, Volume 2, Hardwoods. USDA Forest Service Agriculture Handbook Number 654. Washington, DC. Pp. 570-576.

Department of the Interior (DOI). 1996. Elwha River ecosystem restoration implementation. final environmental impact statement. NPS D-253A. Department of the Interior, National Park Service, Olympic National Park, Port Angeles, WA.

Duda, J. J., J. E. Freilich, and E. G. Schreiner. 2008. Baseline studies in the Elwha River ecosystem prior to dam removal: introduction to the special issue. Northwest Science 82 (Special Issue):1-12.

Fetherston, K. L., R. J. Naiman, and R. E. Bilby. 1995. Large woody debris, physical processes, and riparian forest development in montane river networks of the Pacific Northwest. Geomorphology 13:133-144.

Foiles, M. W., R. T. Graham, and D. F. Olson, Jr. 1990. *Abies grandis* (Dougl. ex D. Don) Lindl. grand fir. *In* R. M. Burns and B. H. Honkala (technical coordinators), Silvics of North America, Volume 1, Conifers. USDA Forest Service Agriculture Handbook Number 654. Washington, DC. Pp. 52-59.

Gilbert, J. and R. Link. 1995. Alluvium distribution in Lake Mills, Glines Canyon Project, and Lake Aldwell, Elwha Project, Washington. Elwha Technical Series

PN-95-4. U.S. Department of the Interior, Bureau of Reclamation, Boise, ID.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An ecosystem prespective of riparian zones. BioScience 41:540-557.

Harrington, C. A., J. C. Zasada, and E. A. Allen. 1994. Biology of red alder (*Alnus rubra* Bong.). *In* D. E. Hibbs, D. S. DeBell, and R. F. Tarrant (editors), The Biology and Management of Red Alder. Oregon State University Press, Corvallis. Pp. 3-22.

Henderson, J. A., D. H. Peter, R. D. Lesher, and D. C. Shaw. 1989. Forested plant associations of the Olympic National Forest. R6 ECOL Technical Paper 001-88. USDA Forest Service, Portland, OR.

Hitchcock, C. L. and A. Cronquist. 1976. Flora of the Pacific Northwest. 3rd printing with further corrections. University of Washington Press, Seattle.

Hughes, F. M. R. 1997. Floodplain biogeomorphology. Progress in Physical Geography 21:510-529.

Johnson, S. L., F. J. Swanson, G. E. Grant, and S. M. Wondzell. 2000. Riparian forest disturbances by a mountain flood—the influence of floated wood. Hydrologic Processes 14:3031-3050.

King, J. E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser Forestry Paper No. 8. Weyerhaeuser Forestry Research Center, Centralia, WA.

Korup, O. L. 2002. Recent research on landslide dams—a literature review with special attention to New Zealand. Progress in Physical Geography 26:206-235.

Latterell, J. J, J. S. Bechtold, T. C. O'Keefe, R. Van Pelt, and R. J. Naiman. 2006. Dynamic patch mosaics and channel movement in an unconfined river valley of the Olympic Mountains. Freshwater Biology 51:523-544.

Lertzman, K. P., G. D. Sutherland, A. Inselberg, and S. C. Saunders. 1996. Canopy gaps and the landscape mosaic in a coastal temperate rain forest. Ecology 77:1254-1270.

Maser, C., S. P. Cline, K. Cromack, Jr., J. M. Trappe, and E. Hansen. 1988. What we know about large trees that fall to the forest floor. *In* C. Maser, R. F. Tarrant, J. M. Trappe, and J. F. Franklin (technical editors), From the forest to the sea: a story of fallen trees. USDA Forest Service General Technical Report PNW-GTR-229. Pacific Northwest Research Station, Portland, OR. Pp. 25-45.

Minore, D. 1979. Comparative autecological characteristics of northwestern tree species—a literature review. USDA Forest Service General Technical Report PNW-GTR-87. Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Montgomery, D. R. and T. B. Abbe. 2006. Influence of log-jam-formed hard points on the formation of valley-bottom landforms in an old-growth forest valley, Queets River, Washington, USA. Quaternary Research 65:147-155.

Naiman, R. J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3:209-212.

Naiman, R. J., K. L. Fetherston, S. J. McKay, and J. Chen. 1998. Riparian forests. *In* R. J. Naiman and R. E. Bilby (editors), River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer, New York. Pp. 289-323.

Nierenberg, T. R. and D. E. Hibbs. 2000. A characterization of unmanaged riparian areas in the central Coast Range of western Oregon. Forest Ecology and Management 129:195-206.

O'Connor, J. E. 2004. The evolving landscape of the Columbia River Gorge: Lewis and Clark and cataclysms on the Columbia. Oregon Historical Quarterly 105:390-421.

O'Connor, J. E., M. A. Jones, and T. L. Haluska. 2003. Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA. Geomorphology 51:31-59.

Pierson, T. C. and J. E. Costa. 1987. A rheologic classification of subaerial sediment-water flows. Reviews in Engineering Geology 7:1-12.

Pojar, J. and A. MacKinnon (editors). 1994. Plants of the Pacific Northwest Coast. Lone Pine Publishing, Vancouver, BC, Canada.

Rot, B. W., R. J. Naiman, and R. E. Bilby. 2000. Stream channel configuration, landform, and riparian forest structure in the Cascade Mountains, Washington. Canadian Journal of Fisheries and Aquatic Science 57:699-707.

SAS Institute Incorporated. 1989. SAS/STAT(R) user's guide. Vol. 2, Version 6 (4th edition). SAS Institute Inc., Cary, NC.

Schuster, R. L., R. L. Logan, and P. T. Pringle. 1992. Prehistoric rock avalanches in the Olympic Mountains, Washington. Science 258:1620-1621.

Schuster, R. L., J. L. Riedel, and P. T. Pringle. 2000. Early Holocene Damnation Creek landslide dam, Washington State, U.S.A. *In* E. Bromhead, N. Dixon, and M. L. Ibsen (editors), Landslides in Research, Theory and Practice. Proceedings of the 8th International Symposium on Landslides 26-30 June, Cardiff, UK. Pp. 1333-1338.

Scott, M. L., J. M. Friedman, and G. T. Auble. 1996. Fluvial process and the establishment of bottomland trees. Geomorphology 14:327-340.

Society for Ecological Restoration International Science & Policy Working Group. 2004. The SER Interntational primer on ecological restoration. Available online at www.ser.org/ (accessed 1 May 2007).

Tabor, R. W. 1987. Geology of Olympic National Park. Pacific Northwest National Parks and Forests Association, Seattle, WA.

USDA, NRCS. 2005. The PLANTS Database, Version 3.5. Data compiled from various sources by Mark W. Skinner. National Plant Data Center, Baton Rouge, LA 70874-4490, USA. Available online at http://plants.usda.gov (accessed 28 January 2004).

Van Pelt, R., T. C. O'Keefe, J. J. Latterell, and R. J. Naiman. 2006. Riparian forest stand development along the Queets River in Olympic National Park, Washington. Ecological Monographs 76:277-298.

Ward, J. V. and J. A. Stanford. 1983. The serial discontinuity concept of lotic ecosystems. *In* T. D. Fontaine, III and S. M. Bartell (editors), Dynamics of Lotic Ecosystems. Ann Arbor Science Publishers, Ann Arbor, MI. Pp. 29-42.

Wiley, K. N. 1978. Site index tables for western hemlock in the Pacific Northwest. Weyerhaeuser Forestry Paper No. 17. Western Forestry Research Center, Weyerhaeuser Company, Centralia, WA.