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The incidence and role of gullies after logging in a coastal redwood forest

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ABSTRACT

The distribution and morphological characteristics of channels were mapped in a redwood forest at Caspar Creek, California, USA, to evaluate the extent to which recent logging has influenced channel conditions in the area. In the North Fork Caspar Creek watershed, second-cycle logging of the early 1990s appears to have triggered increased coalescence of discontinuous gullies within clearcut tributary watersheds, and upstream channel limits in logged watersheds are now located significantly farther upslope than in control watersheds. The magnitudes of observed increases in peakflow after logging are consistent with the change in drainage density. Relations between channel morphological variables and indices of stream power are less well-defined in logged watersheds than in controls, suggesting that logging may have led to disruption of previously established channel forms. Correlations between suspended sediment yields and indices of gully erosion suggest that in-channel erosion associated with hydrologic change is an important source of post-logging sediment at Caspar Creek. Common sediment-control measures, such as use of riparian buffer strips and reduction of road surface erosion, would not be effective for reducing sediment input from this source.

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1. Introduction

Gullying has been triggered by increased runoff and reduced vegetation cover in many areas and is of great concern to land managers (Valentin et al., 2005). Gullies contribute to loss of fertile soils, disrupt transportation networks, and depress water tables in floodplains; and they create persistent sources of sediments that reduce water quality, fill reservoirs, aggrade downstream channels, and impair aquatic habitats. Gullying can increase sediment yields both through incision of existing channels and by expansion of drainage networks into previously unchanneled swales. In the latter case, channel incision may increase transport capacity through the swale, providing hillslope-derived sediment more direct access to downstream channels (Reid, 1989).

Most studies of gullies have been carried out in agricultural lands, grasslands, or arid areas, where the features are most visible and where they most directly challenge land-management activities; gullies in forests are less commonly encountered. Gullying occurred in some areas after conversion of forest to pasture or agriculture (e.g., Gábris et al., 2003; Parkner et al., 2006). In several areas, however, gullies have been identified as major sediment sources within unconverted forest lands. Often forest gullies are associated with road drainage or with areas compacted by logging equipment (e.g., Weaver et al., 1995; Croke and Mockler, 2001), but in other cases gullying appears to be a more generalized response to forest management (Heede, 1991) or to temporary vegetation changes upslope of the forested area (Vanwalleghem et al., 2003) or is an inherent feature of the forested setting (Parkner et al., 2007).

In part because of the long duration of forest management cycles and the inability to detect forest gullies on historical aerial photographs, the incidence of forest gullies and their relation to forest management remain poorly understood, particularly in settings where overland flow is uncommon. Observed changes in gully activity with forest conversion and subsequent reforestation (e.g., Gábris et al., 2003; Parkner et al., 2006) indicate that catchment vegetation can influence gullying and that those influences vary by vegetation type. Forest vegetation commonly has larger roots and produces larger quantities of coarse litter than other vegetation types, and forests provide woody debris that retains sediment on hillsides and in small channels (Maser et al., 1988). Vegetation type is also expected to influence runoff volumes (Bosch and Hewlett, 1982), peakflow magnitudes (Guillemette et al., 2005), and snowmelt timing (Winkler et al., 2005), each of which could influence gully erosion rates during short-term perturbations in vegetation cover. Vegetation can also regulate gully activity at a smaller scale. For example, Molina et al. (2009) have shown that herbaceous and shrubby vegetation on gully floors is effective in trapping sediment.

During recent forestry planning efforts in NW California, unanswered questions were raised concerning the role of management-related channel erosion in sediment production. This paper presents the results of a study implemented in the Caspar Creek Experimental Watersheds of north coastal California, USA, to (i) evaluate the distribution of incised channels and associated headcuts in the area; (ii) assess the relative importance of gully erosion as a sediment

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source there; and (iii) identify potential influences of forest land management on the extent and character of the gullied reaches.

2. Study area

The Caspar Creek Experimental Watersheds (N39°21′ W123°44′) include the 424-ha South Fork and 473-ha North Fork tributaries of Caspar Creek, which drains to the Pacific Ocean 10 km south of Fort Bragg, CA (Fig. 1). The Caspar Creek catchment is deeply incised into a flight of uplifted marine terraces formed over more than 300,000 years on Franciscan sandstone and shale (Merritts et al., 1991). Elevation in the experimental watersheds ranges from 37 to 320 m, with hillslopes steepest near the stream channel and becoming gentler near the broad, rounded ridgetops. About 35% of the slopes are lower than 17° and 7% are steeper than 35°. Longitudinal channel profiles are generally concave, but many include low-gradient reaches (1° to 5°) immediately followed by relatively short steeper reaches (5° to 20°). Mainstem channels and many tributary segments are bordered by narrow valley flats. Radiocarbon dating of charcoal in 3- to 4-m-deep valley fills in upper reaches of the North Fork suggests that deposition began about 7000 ^{14}C YBP and proceeded episodically through the middle to late Holocene (Steven Reneau, Los Alamos National Laboratory, personal communication, 1989).

The climate is typical of coastal watersheds in the region: winters are mild and wet, while summers are mild and dry. About 95% of the average annual precipitation of about 1200 mm occurs in October through April, and most rain falls in storms of long duration but low intensity. Snow is uncommon.

Soils are predominantly gravelly to sandy loams with a typical depth of 1.5 m. The upper meter of the most common soils includes 25 to 50% gravel and cobble and 30 to 50% clay and silt, and has a bulk density of 1.4 to 1.6 Mg m^{-3} (Wosika, 1981). Subsurface stormflow is rapid, and saturated areas are uncommon and drain quickly after storms. Soil pipes are present in most swales and transport a substantial discharge of storm flow to low-order channels (Albright, 1991). Channel flow often becomes spatially intermittent within a few weeks of a winter storm in catchments smaller than 20 ha (L. Keppeler, USFS, personal communication, 2008).

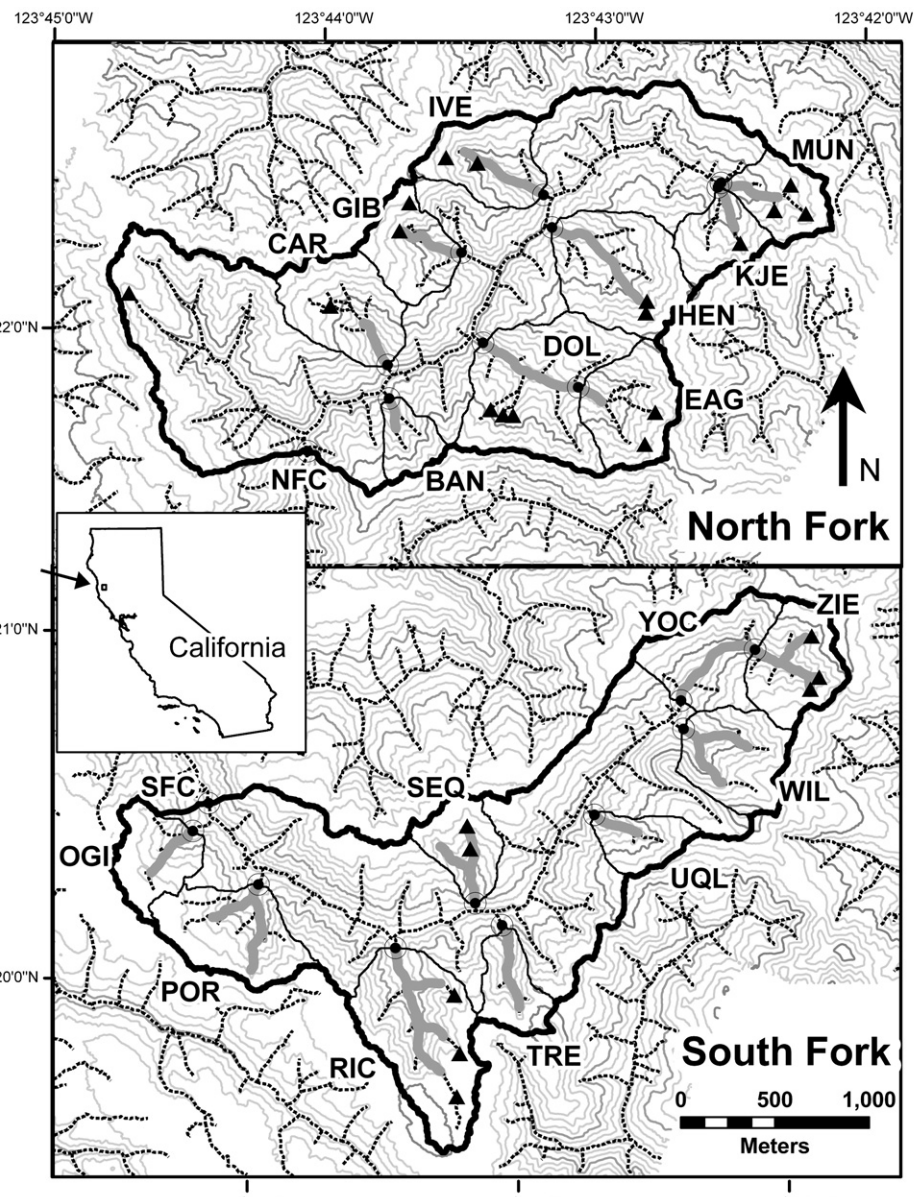

Fig. 1. The Caspar Creek experimental watersheds. Tributaries in which headcuts were mapped are shown in gray, dots indicate location of gaging stations, and triangles indicate locations of mapped channel limits.

Both experimental watersheds are densely forested with second- or third-growth stands dominated by coastal redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*). The entire study area was first logged between 1860 and 1904 using cleared-out channels as routes for log transport (Napolitano, 1998). The low incidence of old-growth wood in today's channels reflects this use, presenting a contrast to the high volumes of very large woody debris present in channels draining old-growth redwood forests of the region (e.g., Keller et al., 1995).

The Caspar Creek Experimental Watersheds were established in 1961 as a long-term research site run jointly by the California Division of Forestry and Fire Protection and the U.S. Forest Service (USFS) Pacific Southwest Research Station. Weirs and gaging stations were constructed by November 1962 on the North and South Forks. After an initial period of calibration between the two watersheds, roads were constructed in the South Fork in 1967, and nearly two-thirds of the stand volume was selectively logged from 1971 to 1973. Tractors commonly dragged logs down tributary valleys, once again severely disturbing some channels.

Twelve years after South Fork logging, thirteen additional gaging stations were constructed in tributaries and along the main stem of the North Fork. The new stations underwent calibration for 4 years. Thirty-seven percent of the North Fork watershed was then roaded, clearcut, and cable-yarded from ridgetops between 1989 and 1992. Selectively logged buffer strips were left around channels with drainage areas of greater than about 10 to 12 ha, and three subcatchments (HEN, IVE, and MUN, Fig. 1) were left as mature second-growth controls within the North Fork watershed. All watersheds but BAN and HEN included some roads constructed long before calibration began, and both new and old roads were located near ridges.

Both episodes of experimental logging resulted in increased runoff and sediment yield, followed by substantial recovery within a decade of logging (Ziemer, 1998). In the North Fork watersheds, increases in sediment production were correlated with increases in storm runoff (Lewis et al., 2001), which were attributable largely to reduced rainfall interception and transpiration after logging (Reid and Lewis, 2007). Ten new gaging stations were constructed on South Fork tributaries in 2000 in preparation for a third experiment.

Stands representing three broad categories are now present in the North and South Fork watersheds. In North Fork control watersheds, the overstory is dominated by 100- to 140-year-old redwoods and Douglas-firs with diameters at breast height (DBH) of about 70 to 150 cm. A subcanopy composed of hardwoods (principally tanoak, *Lithocarpus densiflora*) and small conifers is present at most sites, and shrubs, ferns and herbs provide a discontinuous ground cover. Total stand density for stems larger than 12.7 cm DBH is typically on the order of 500 stems/ha, with a basal area of about 100 $m^2\ ha^{-1}$ as of 1998. South Fork stands reflect the selection logging of the early 1970s, having a higher density of small trees than North Fork stands but including a similar range of stem sizes. South Fork stands typically have 600 to 1200 stems/ha and basal areas of 65 to 85 $m^2\ ha^{-1}$ as of 2009. The North Fork watersheds logged in 1989–1992 were clearcut, leaving only a disturbed and discontinuous cover of shrubs and herbs. Regrowth has been rapid, and herbicides were applied to watersheds EAG and GIB in 1994 and again in 1996 to control growth of shrubs and hardwoods, while logged watersheds BAN, CAR, and KJE were not treated. Logged watersheds were then thinned in 1998 (KJE) or 2001, leaving about 800 to 2000 stems/ha (basal area: 3 to 5 $m^2\ ha^{-1}$) and reducing crown area to about 20% of that present before thinning.

Most tributary segments with catchments larger than 1.9 ha show evidence of active incision characteristic of gullying, such as steep, raw banks, eroding headcuts, quasirectangular cross sections, and low width–depth ratios (Fig. 2). Old-growth roots often span channels or form headcut lips, and many old-growth stumps are now being undermined by gully-bank erosion and are toppling into channels.

Fig. 2. Headcut in MUN tributary, North Fork Caspar Creek. Note knapsack for scale; headcut is 1 m high.

Much of the valley-axis area thus had supported trees for centuries, and gullies have expanded significantly since the trees were cut during first-cycle logging. Either previous gullies were limited in extent or earlier episodes of extensive gullying had stabilized by about 400 years ago. Many gullies in both confined reaches and valley flats excavate saprolite, also suggesting that the current extent of gullying is unprecedented.

At gully headcuts, the stream typically flows over a lip reinforced by a large root or piece of woody debris and scours a plungepool below. Several modes of headcut erosion are observed in the area: (i) gradual backwasting of the exposed face through ravel, spalling, and tractive erosion, (ii) sapping or tunnel erosion, with rapid retreat occurring when the upstream tunnel enlarges enough that a portion of the roof collapses, (iii) block failures induced by undercutting from backwasting, plungepool erosion, or sapping, and (iv) rapid tractive erosion when a reinforced lip loses its influence, causing a sudden drop in base level to the upstream reach. Most headcuts and associated plungepools show complex forms modified by woody debris, roots, bedrock, boulders, and in-place or toppled bank vegetation; few exhibit the regular morphology typical of grassland gullies. Little vegetation other than moss is present in growth position on gully floors.

3. Methods

The study relies on four kinds of data: (i) measurements of gully distribution and characteristics recorded during field surveys carried out during 2000–2002 and 2006–2008; (ii) measurements of process rates monitored within a subset of the gullies; (iii) sediment gaging records from gullied tributaries; and (iv) information from earlier studies of surface erosion and landslide distribution in the area.

3.1. Gully distribution and dimensions

Channel characteristics were mapped along the main axes of 16 tributaries from near the mouth of the channel to a point above which the drainageway is no longer primarily in the form of an active channel; this aspect of the study is described in more detail by Dewey (2007). Above most of the upstream mapping points in North Fork control channels and South Fork channels are 1 to 4 ha of swale in which either unchanneled reaches predominate or most of the channel is inactive and filled with duff. Additional pipe collapses and discontinuous gullies occur upstream of mapped reaches, and mapped reaches include occasional unincised zones. During this phase of the study, the upstream end of the channel could not be readily found in some clearcut watersheds where channels were obscured by dense regrowth and logging debris. Hillslope gullies and subsidiary tributaries generally were not mapped, but both branches of the main tributary channel were mapped if the dominant fork could not be identified.

In North Fork tributaries, headcut locations and channel width and depth measurements were added to a preexisting channel map. In the South Fork, channels had not previously been mapped, so tributary thalwegs were mapped relative to tapelines established from surveyed benchmarks. Tapeline slope was calculated from surveyed endpoint locations or measured with a hand level; and a stadia rod was used to measure bank height, channel width, and thalweg elevation relative to the tapeline.

Bank-to-bank width and bank-to-thalweg depth were measured at 1074 locations along 3290 m of valley axis in eight North Fork tributaries and at 2124 locations along 5670 m in eight South Fork tributaries. Depth is reported as an average of measurements taken relative to the left and right banks, and depth and width are interpolated linearly between measurement points to allow estimation of average values for 25- and 50-m channel segments. In North Fork tributaries, the product of depth, width, and channel increment length is summed by 2-m channel pixels to estimate channel-segment volumes. South Fork volumes are estimated by summing values for measurement-bounded channel increments. Measurements from 18 surveyed cross sections indicate that the product of thalweg depth and bankfull width overestimates cross-sectional area in these tributaries by a factor of 1.40 (95% confidence interval: ± 0.09), with no significant dependence on width-to-depth ratio, and this value is used as a correction factor for estimating volumes.

Each mapped channel contains many vertical or near-vertical steps in its long profile. These features were classified as headcuts for this study if the step face included some component of material other than woody debris or bedrock. The location and height (relative to the plungepool nadir) of almost all headcuts higher than 0.3 m were recorded, but only headcuts higher than 0.44 m are considered in this analysis in order to ensure a consistent resolution between tributaries. The distribution of recorded heights suggests that 0.26- to 0.44-m headcuts would account for 15 to 20% of the headcuts higher than 0.26 m, or about 7 to 10% of the total headcut height, so exclusion of these features from the data set is not expected to substantially influence conclusions. A 2-m digital elevation model (DEM) was used to estimate drainage area and elevation at each channel pixel in the North Fork, while results from the South Fork are based on information from a 10-m DEM.

To evaluate the extent of the channel network, upstream channel limits were subsequently mapped in 10 forested tributaries and 7 clearcut tributaries in North Fork watersheds and in 8 South Fork catchments (Fig. 1). Because channels are discontinuous in their upstream reaches, the limit was defined for this portion of the study as the upper boundary of the upstream-most channel segment longer than 5 m that has well-defined banks and appears to have carried flow within the previous decade.

We evaluate the distribution of incised channels and associated headcuts by testing for patterns of association between headcut characteristics or channel form descriptors and such factors as drainage area, stream power, and treatment category. Because channel characteristics vary by position in the watershed and because different sections of each watershed were logged or mapped (Table 1), long-profile variations in channel and headcut characteristics must be accounted for if differences in characteristics between treatment groups (i.e., control, recently clearcut North Fork, and selectively logged South Fork watersheds) are to be validly identified. To do so, each channel or headcut characteristic identified for 25- or 50-m reaches within a treatment group was first regressed individually against catchment area, channel gradient, and a stream power index (the product of catchment area and segment gradient, as defined by Montgomery and Dietrich, 1989). If a significant relationship to one of these variables was found, multiple regression was used to determine if treatment is an additional significant variable, with significance assessed at the 0.05 level throughout the sequence of analyses. Comparisons are restricted to data from

Table 1
Mapped tributaries at Caspar Creek; channel attributes are reported here only for the mapped portion of the channel network.

	Gaged area (ha)	Percent logged	Percent roads[a] 1986	1995	Gage record	Area above survey (ha)	Total channel length (m)[b]	Buffer strip length (m)	Surveyed channel length (m)	Surveyed channel volume (m^3)	Surveyed bank area (m^2)	Headcuts >0.44 m
North Fork clearcut 1989–91												
BAN	10	95	0.0	3.5	1985–1995	5.1	875	88	157	63	106	19
CAR	26	96	4.7	6.4	1985–now	14.2	2343	242	284	611	646	15
DOL[c]	77	36	–	–	1985–now	26.6	–	n.a.	586	1243	1174	37
EAG	27	100	0.8	4.6	1985–now	8.9	2406	105	149	339	383	6
GIB	20	100	5.2	7.8	1985–1995	1.2	2115	107	360	312	427	41
KJE	15	97	0.3	6.3	1985–1995	3.7	1179	235	253	1511	880	14
North Fork control												
HEN	39	0	0.1	0.1	1985–now	3.7	3341	n.a.	675	640	821	78
IVE	21	0	7.6	7.6	1985–now	3.4	948	n.a.	494	512	625	53
MUN	16	0	5.2	5.2	1985–1995	6.9	1293	n.a.	330	633	467	21
South Fork selectively cut 1971–73												
OGI[d]	18	50	–	–	2000–now	5.2	–	n.a.	350	337	495	18
POR	32	54	–	–	2000–now	1.7	–	n.a.	780	1207	1135	41
RIC	49	67	–	–	2000–now	1.3	–	n.a.	1144	1356	1477	75
SEQ	17	67	–	–	2000–now	1.2	–	n.a.	668	845	810	45
TRE	14	67	–	–	2000–now	1.8	–	n.a.	489	464	665	33
UQL	13	67	–	–	2000–now	3.4	–	n.a.	269	258	316	42
WIL	26	67	–	–	2000–now	3.5	–	n.a.	699	687	867	94
YOC[c]	53	67	–	–	2000–now	25	–	n.a.	575	645	750	41
ZIE	25	67	–	–	2000–now	1.4	–	n.a.	694	458	706	57

[a] Percent of area in roads and landings; values are approximate due to potential instability of drainage patterns on ridge-top roads.
[b] Includes all sub-tributaries, as estimated from DEMs on the basis of expected headwater catchment area; value listed for DOL is exclusive of length in EAG.
[c] DOL is located downstream of EAG, and YOC is downstream of ZIE; surveyed values listed for DOL and YOC pertain only to the segment of the watershed below the upstream gage.
[d] OGI includes 27% private land that has been selectively logged several times since 1971.

watershed areas of 3 to 30 ha to ensure that samples are available from similar locations in both logged and control watersheds.

3.2. Gully erosion rates

Tributaries YOC, ZIE, and MUN (Fig. 1) were selected for monitoring of headcut changes over a multi-year period using one of three methods. Five headcuts (group I) were surveyed in detail with an electronic total station in the summers of 2000 and 2002. The resulting maps are capable of revealing local changes of more than about 5 cm. At six other headcuts (group II), transects were surveyed first by survey laser and later by rod and tape to measure headcut retreat and bank erosion upstream and downstream of the headcut; survey error is estimated to be about 2 cm. An additional 41 headcuts (group III) were visually checked for obvious retreat, with changes >30 cm expected to be visible. Headcuts were revisited during the summer of 2003 and in February 2004, and additional measurements were made at three rapidly eroding headcuts. Nine headcuts from groups I and II at which benchmarks could be relocated were again surveyed in 2006 and 2008 using an electronic total station. Cross-section measurements from groups I and II also allowed monitoring of bank erosion on 15 near-vertical banks between the summers of 2000 and 2002; 12 of the 15 measurements are from banks within 4 m downstream of a headcut. Flow conditions over the monitoring period ranged widely: the highest flow recorded at IVE during 24 years of monitoring occurred in December 2005, while all other years produced maximum flows with recurrence intervals of less than 2 years.

During the autumn of 2000, paint was applied to roots at the point at which each emerged from a headcut face to allow long-term monitoring of bank recession at several headcuts. Distances between the wall surface and the painted portions of roots were measured at 43 points on four headcut overfalls during July 2008.

In calculations of erosion rates, a bulk density of 1.5 Mg m^{-3} is assumed when converting rates from units of $m^3\ y^{-1}$ to Mg y^{-1}.

3.3. Suspended sediment transport at gaging stations

We use records from nine tributary gaging stations in the North Fork watershed (Fig. 1; Table 1) to evaluate variations in annual suspended sediment yield as they may relate to gullying; results of the suspended sediment study evaluated by storm period are reported elsewhere (Lewis, 1998; Lewis et al., 2001). Automatic sediment samplers at each gage are programmed to sample at predetermined turbidity levels. These sediment measurements allow ongoing recalibration of the turbidity record at each gage in order to produce a continuous estimate of suspended sediment concentration during storms (Lewis, 1996), and transport rates are then computed from discharge and concentration. Measured storms account for 90 to 99% of sediment output in most years (Jack Lewis, USFS, personal communication, 2007), with the highest percentages for years with large flows, so the approach is expected to account for at least 95% of the suspended load during the period analyzed.

For the current study, analysis requires annual loads rather than storm-period loads, so storm loads had to be estimated at several stations during periods with missing record. Loads at individual stations were estimated for missing portions of the pre-logging record using correlations between peakflow and storm sediment load or between loads at nearby gages if peakflow data were missing. Regressions are not expected to be stable during the post-logging period, so missing values after logging were estimated using ratios between the target storm load and temporally adjacent storm loads at stations with records for the missing storm. Imputed values account for about 4% of the total suspended sediment load.

3.4. Other erosion studies

The incidence of landslides and treethrows mobilizing more than 7.5 m^3 has been recorded in the North Fork watershed since 1986 through "large-event surveys" carried out during post-storm channel inspections. Each event is located on a channel map with reference to existing benchmarks, and the scar is diagramed and dimensions measured. Associations with roads or treethrows are noted if present, and the volume of displaced sediment still present on the scar is estimated.

Surficial erosion has also been evaluated in the area. Rice (1996) reported results of void measurements on erosion plots at 175 hillslope sites and 129 road sites distributed randomly through the North Fork watershed after completion of second-cycle logging. Sample units on logged and unlogged hillslopes were circular 0.08-ha plots, while those on roads were 1.5-m-wide segments of the road prism oriented perpendicular to the road centerline. Processes assessed on plots include rilling, sheet erosion, and soil displacement from yarding. Rice weighted erosion plot data according to the proportion of the sub-watershed logged and the road length present in each and reported results as average total erosion per unit area of each sub-watershed.

Rice's results require reevaluation for the current study because several sub-watersheds had experienced different durations since logging at the time of the survey (1995). Given the large reported differences in erosion between logged and unlogged sites (Rice, 1996), most soil displacement appears to be associated with treatment, so Rice's estimates for rates of road and hillslope surface erosion are here recalculated as erosion per year since the onset of construction of new logging roads in the treated watersheds. Rates for the control watersheds are also calculated assuming a 5-year period of visibility rather than the 10-year period implicitly assumed by Rice (1996).

For the calibration period, hillslope surface erosion is estimated simply as the mean of the rates calculated for the post-calibration period in the three control watersheds. This approach cannot be adopted to estimate road-related erosion during the calibration period because road erosion for the post-calibration period in both logged and control watersheds reflects the period of high-intensity use during logging. Results from Reid and Dunne (1984) suggest rates of surface erosion on gravel-surfaced logging roads are about 75 times higher during high-intensity use periods than during periods of light use. Log hauling typically took place over a 4-month period within each logged watershed, and mainline roads in all watersheds would have undergone longer periods of heavy use as neighboring units were logged. Road erosion rates are assumed to be 75 times higher than "background" road erosion rates for a 4-month period during the post-calibration period, and the corresponding rate for light-use periods is then calculated algebraically from the road erosion plot data (i.e., $plot\ total = (0.33\ year \times 75x) + [(post\text{-}calibration\ duration - 0.33\ year) \times x]$, where x = rate for the light-use period). The mean of estimated light-use rates calculated per unit area of road is then applied to the area of roads present during the calibration period in each watershed.

4. Results

4.1. Gully distribution and characteristics

Gully headcuts are common along all mapped valley axes (Fig. 3, Table 1), with some present in catchments of <1 ha. There are 284 mapped headcuts higher than 0.44 m in North Fork tributaries and 446 in South Fork tributaries, indicating average frequencies of 8.6 and 7.9 headcuts per 100 m of channel, respectively. Differences in gully characteristics between logged and control watersheds are not evident to casual observation (e.g., Fig. 3), indicating that any major

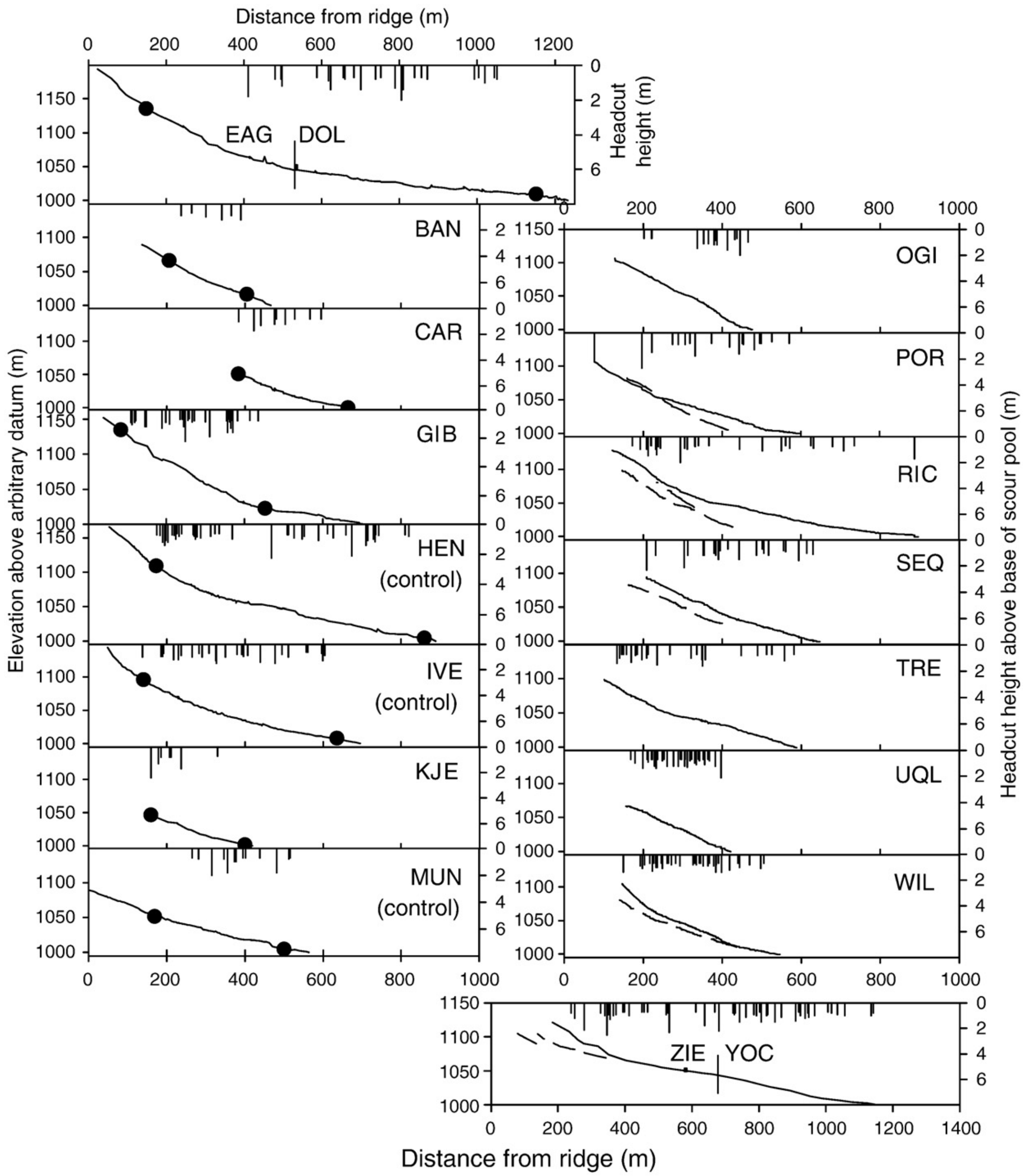

Fig. 3. Surveyed valley-axis profiles in gaged tributaries. Tics indicate the locations and heights of headcuts along the main tributary channel, and dashed lines show profiles of additional mapped branch tributaries. Dots on North Fork profiles indicate the limits of headcut mapping. For clarity, mapped headcuts shorter than 0.64 m are omitted. See Table 1 for watershed descriptions.

incision episode predated second-cycle logging. In particular, the logged KJE catchment was noted to have exhibited particularly well-developed gullies even before the recent logging.

Headcut characteristics are assessed for 50-m channel reaches; analysis of shorter reaches would provide too few headcuts in each sample unit. Headcut height (h) in North Fork tributaries increases weakly but significantly with channel-segment gradient (s) ($\log h = -0.34 + 0.58s$, $p < 0.001$, $r^2 = 0.064$), and the relation shows no significant difference between logged and control tributaries. In contrast, mean headcut spacing decreases significantly with increasing gradient (Fig. 4), and headcuts in control watersheds are spaced significantly more closely than in logged watersheds. Although variance is high, control watersheds show a tendency for the proportion of channel elevation drop accounted for by headcuts to increase with increasing catchment area (Fig. 4C), while logged watersheds show no significant increase (Fig. 4D). For channel segments with catchment areas larger than 10 ha, control watersheds show the mean proportion of elevation drop from headcuts to be 0.53 ± 0.09, compared to 0.26 ± 0.09 in logged watersheds.

Sample frequencies allow assessment of channel characteristics in reaches shorter than those required for headcut assessments. Comparisons of morphological attributes in 25-m channel reaches in control and logged watersheds show patterns similar to that of Fig. 4D: the systematic variations in width, depth, and cross-sectional

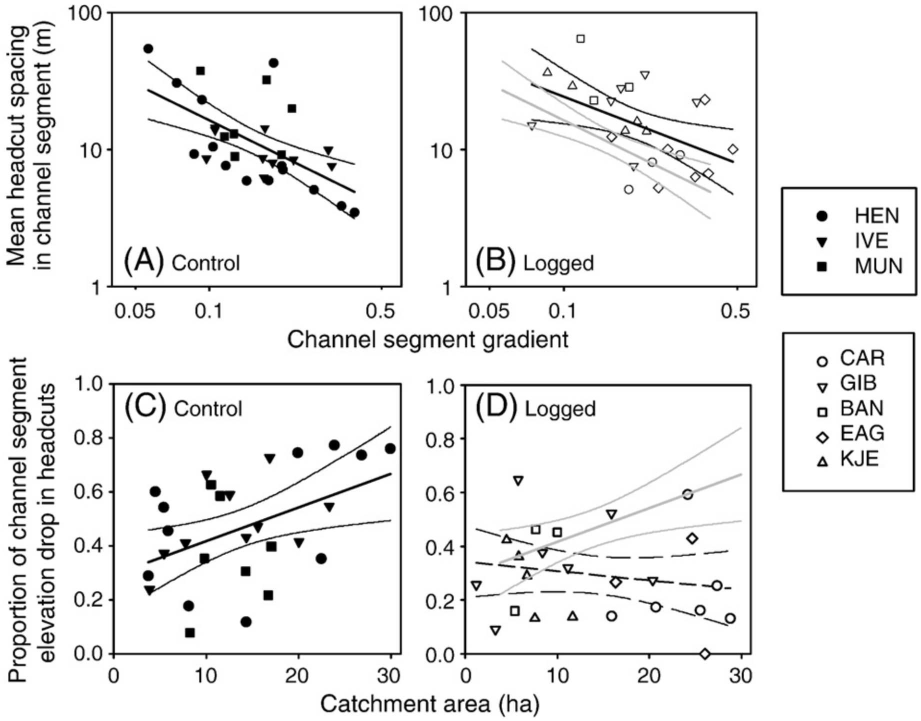

Fig. 4. Headcut spacing as a function of channel gradient in 50-m reaches of North Fork (A) control ($r^2=0.36$) and (B) logged ($r^2=0.23$) tributaries; and relative importance of elevation drop from headcuts in (C) control ($r^2=0.20$) and (D) logged ($r^2=0.03$) tributaries of North Fork Caspar Creek. The gray lines in Fig. 4B and D depict the regression and 95% confidence band for controls. Dashed lines indicate relations not significant at the 0.05 level.

area with stream power index expressed in control tributaries are not evident in recently logged tributaries (Fig. 5A). Relations between these attributes and watershed area, however, are strongly expressed in the pervasively gullied KJE tributary (Fig. 5B), in which gullies appear to have coalesced before monitoring began and which exhibits no significant relations to stream power index.

Results for South Fork tributaries, which were selectively logged in the early 1970s, are generally intermediate to those in North Fork logged and control watersheds. Headcut spacing in 50-m reaches and the proportional elevation drop accounted for by headcuts are most similar to those in logged North Fork watersheds (Fig. 6). Morphological data from South Fork tributaries generally show higher variance than found for either logged or control North Fork channels, which may in part result from the use of a l0-m DEM for the analysis rather than the 2-m DEM used for North Fork tributaries.

Mapping of upstream channel limits in North Fork control watersheds shows a mean stream power index of 0.69 ± 0.12 ha at the channel head (Fig. 7, Table 2). Results for the South Fork watershed (0.61 ± 0.09 ha) are not significantly different from those for North Fork control watersheds, while values for clearcut North Fork watersheds (0.34 ± 0.10 ha) are significantly lower than those in either control watersheds or South Fork tributaries. The catchment area at the head of forested channels averages 1.9 ± 0.3 ha, compared to 1.2 ± 0.5 ha for logged tributaries, representing a 28% increase in drainage density within 30-ha watersheds.

4.2. Rates of erosion at headcuts and streambanks

Measured rates of headcut retreat are highly skewed in part because of differences between activity levels at headcuts held in place by roots or woody debris and those not impeded by such features. Of the 52 headcuts observed over a four-year period in MUN, YOC, and ZIE tributaries, three migrated rapidly (>30 cm y^{-1}) during at least one year, for a total of 4.8 m during four headcut-years. The other 204 headcut-years produced no rapid retreat. The resulting mean rate of rapid retreat for all 52 monitored headcuts is 4.8 m for 208 headcut-years, or 2.3 cm y^{-1} per headcut.

For the subset of 11 headcuts that were surveyed in more detail between 2000 and 2002 or 2008, displacement totaled 158 cm over 64 headcut-years that exhibited no rapid retreat, producing a mean retreat of 2.5 cm y^{-1}. Individual retreat rates ranged from 0 to 30 cm y^{-1}, with two headcuts showing no retreat over the 8-year period. Recession monitored around painted roots over an 8-year period indicated an average retreat of 0.7 cm y^{-1} for 32 headcut-years. The combined estimate for gradual retreat is thus 1.9 cm y^{-1}, and the estimated total retreat rate is 4.2 cm y^{-1} with an expected accuracy of about ±50%. Data are too few and variance too high to isolate the effect of the 25-year recurrence interval storm of December 2005. Field observations suggest that many of the changes in headcut location noted between 2002 and 2006 may have resulted from the storm, but that the storm did not cause widespread or severe channel disruption.

As is the case for headcuts, banks show a skewed distribution of rates. Two monitored banks eroded rapidly (6 and 8 cm y^{-1}), while eight showed rates of <1 cm/y; retreat averaged 1.6 ± 1.2 cm y^{-1}. Erosion generally occurred either by block failure–often associated with undercutting–or by more widespread but gradual backwasting and spalling.

4.3. Suspended sediment yields

Lewis (1998) demonstrated that, with the exception of KJE, storm-based sediment yields increased significantly above expected levels after logging; these patterns are evaluated in more detail by Lewis et al. (2001). For the present study, we evaluate annual yields to assess the relative importance of individual watersheds as sediment sources. Mean annual suspended sediment yields at North Fork tributary gaging stations range between 2 Mg km^{-2} y^{-1} at watershed BAN before logging and 68 Mg km^{-2} y^{-1} at KJE after logging (Table 3).

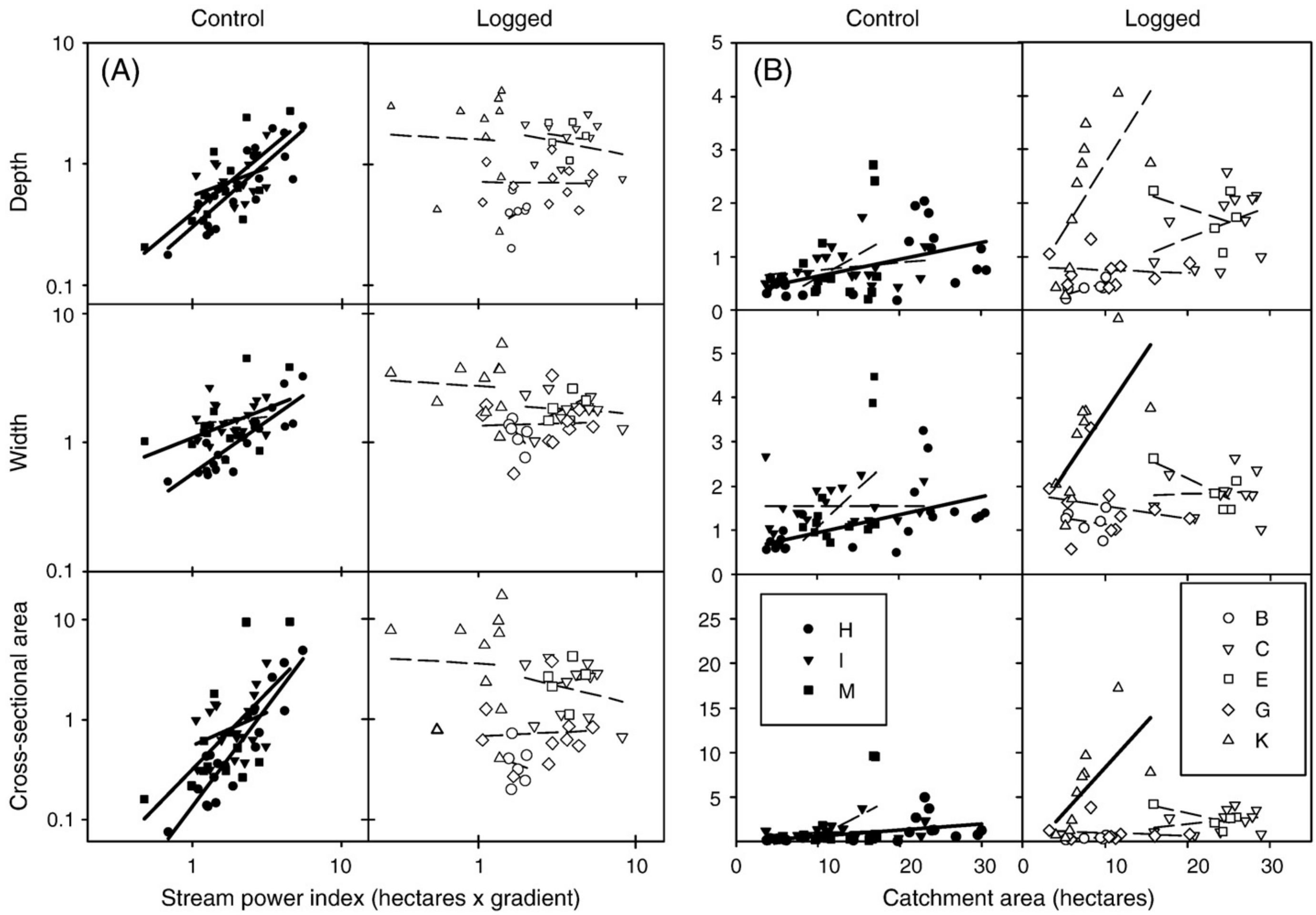

Fig. 5. Variation in mean segment depth (m), width (m), and cross-sectional area (m^2) with (A) stream power index and (B) catchment area in control and logged tributaries of North Fork Caspar Creek. Relations significant at the 0.05 level are depicted by solid lines.

4.4. Rates of erosion from other sources

Plot erosion data reported by Rice (1996) and here recalculated to reflect the post-calibration period reveal strong differences between logged and control watersheds. Logged watersheds show road and hillslope soil displacement rates averaging 2600 ± 1170 Mg km^{-2} y^{-1}, with 6 to 33% of the individual watershed totals associated with road erosion. In control watersheds, displacement averages about 8% of that calculated for the logged watersheds over the analogous period (Table 3), and 0% to 76% is associated with road erosion. Erosion on hillslope plots in control watersheds averages 67 ± 61 Mg km^{-2} y^{-1}. These calculations assume that all erosion voids are visible for 5 years in control watersheds. If the period of visibility is actually longer, as assumed by Rice (1996), the difference between displacements in logged and control watersheds would be accordingly greater. Hillslope and road erosion rates for the calibration period are highly uncertain. Differences in estimated displacement from roads during the calibration and post-calibration periods reflect the increase in road area in the treated watersheds and the expected influence of heavy road use in both treated and control watersheds. Overall, expected road sediment after the onset of road construction increased on average by factors of 16 in treated watersheds and 6 in controls.

Large-event surveys in the gaged watersheds disclosed 8 events capable of contributing sediment to streams during the calibration period and 25 in the post-calibration period. Mapped events were associated with major storms in 1986 (5 events), 1990 (4 events in two storms), 1993 (7 events), and 1995 (17 events in two storms). Field-based estimates for each of these events indicate that an average of about 25% of the sediment displaced was transported off-site. Annualized average volumes of off-site displacement from large events during the post-calibration period (Table 3) are not significantly different at the 0.05 level between treated watersheds (19 ± 14 Mg km^{-2} y^{-1}) and controls (26 ± 2 Mg km^{-2} y^{-1}).

5. Interpretation and discussion

Results of the field study are here interpreted to address three questions: (i) What is the relative importance of gully erosion between logged and forested tributary watersheds at Caspar Creek? (ii) How important is gully erosion relative to other sediment sources in the area? (iii) What mechanisms might contribute to differences in the extent and importance of gully erosion between logged and unlogged watersheds?

5.1. Sediment production from gully erosion in logged and forested tributaries

Once the distribution of channel characteristics and their associations with land-management categories are identified, it is possible to extrapolate information from the sampled portions of a watershed to the watershed as a whole. Measured headcut and bank erosion rates can then be applied to the channel network expected in each setting to allow comparison of average sediment production rates from gully sources typical of forested North Fork watersheds, recently clearcut

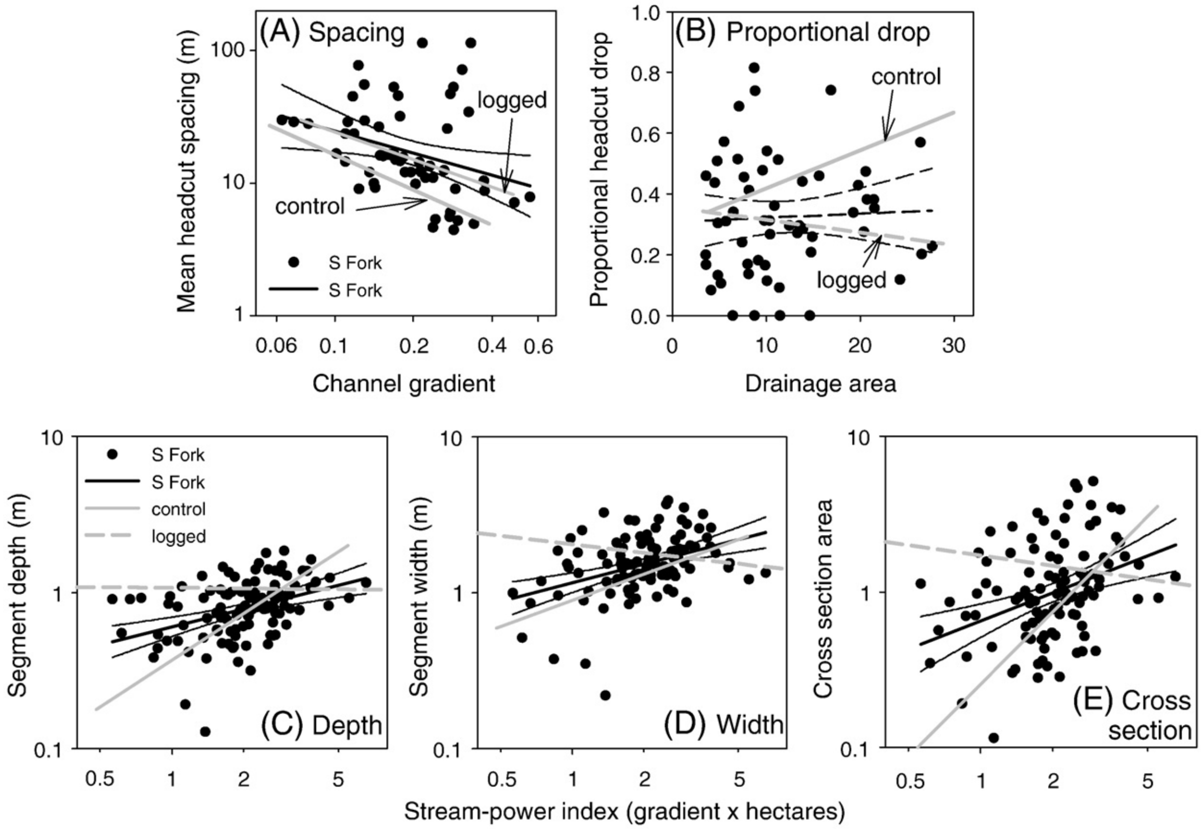

Fig. 6. Patterns of headcut distribution in South Fork tributary channels, and morphological characteristics of South Fork channels. Relations shown in gray depict analogous relations for North Fork tributaries (pooled regressions from Figs. 4 and 5), and relations significant at the 0.05 level are depicted by solid lines.

North Fork watersheds, and selectively logged South Fork watersheds. Calculations of sediment production from bank and headcut erosion are based on sparse data from a limited period, so estimates are not reliable. However, estimated sediment input rates are useful for indicating the potential magnitude of sediment contribution from the gullies and for assessing relative contributions among the three watershed treatment categories.

Sediment production by retreat of headcuts higher than 0.44 m in control watersheds can be estimated if we assume (i) the area of each eroding headcut face is equivalent to the product of the headcut height (relative to the base of the plungepool) and the channel width measured immediately downstream; (ii) the calculated average retreat rate of 4.2 cm y^{-1} for monitored headcuts applies to all headcuts higher than 0.44 m; and (iii) headcut frequency and dimensions in unmapped channels are similar to those in mapped reaches of similar size. Estimated sediment input from this source is then 28 Mg km^{-2} y^{-1} in North Fork control tributaries smaller than 30 ha (Table 2), with 19% of that sediment originating in channels draining areas of 1.9 to 3 ha, which were not characterized in control watersheds during the gully survey. Because headcut face areas are calculated as the product of channel width and the face height above the base of the plungepool, plungepool erosion is implicitly included as a component of headcut erosion.

A portion of the sediment eroded from headcuts and plungepools is deposited immediately downstream on the depositional downstream lip of the plungepool. Lip aggradation is estimated to account

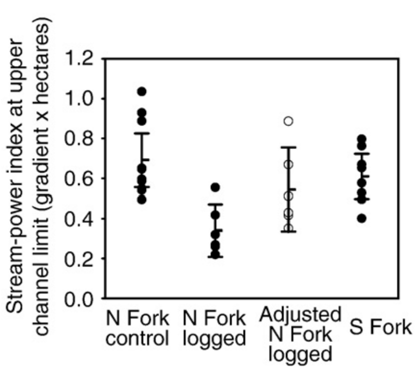

Fig. 7. Distribution of stream power indices at the upper limits of tributary channels. Error bars indicate the 95% confidence interval around the means (horizontal lines). "Adjusted" values account for hydrologic change after North Fork logging (see text Section 5.3.1).

Table 2
Comparison of channel characteristics for three watershed categories; dimensions represent means for 25-m channel segments; 95% confidence intervals are indicated for means.

Attribute	North Fork		South Fork
	Control	Clearcut[a]	
Catchment area at channel head (ha)	1.9 ± 0.3	1.2 ± 0.5	2.3 ± 1.0
Stream power index at channel head (ha)	0.69 ± 0.12	0.34 ± 0.10	0.61 ± 0.09
Channel width: mean at 3 to 7 ha (m)	0.97 ± 0.34	1.31 ± 0.38	1.37 ± 0.26
Channel width: mean at 15 to 25 ha (m)	1.83 ± 0.48	1.76 ± 0.25	2.16 ± 0.38
Channel depth: mean at 3 to 7 ha (m)	0.49 ± 0.07	0.53 ± 0.23	0.72 ± 0.11
Channel depth: mean at 15 to 25 ha (m)	1.16 ± 0.35	1.35 ± 0.40	1.02 ± 0.18
Estimated headcut erosion (Mg km^{-2} y^{-1})	28	50	37
Estimated plungepool deposition (Mg km^{-2} y^{-1})	7	12	9
Estimated bank erosion (Mg km^{-2} y^{-1})	54	73	66
1992–95 average suspended load (Mg km^{-2} y^{-1})	25 ± 17	39 ± 20	-

[a] Exclusive of watershed KJE.

Table 3
Estimated rates of sediment displacement and suspended sediment yields in North Fork sub-watersheds.

Site	Area (ha)	Years in category[a]	Suspended sediment yield	Road plot erosion[b]	Hillslope plot erosion[b]	Landslides and treethrows[c]	Gully erosion[d]
			(Mg km^{-2} y^{-1})				
Treatment watersheds, calibration period[a]							
BAN	10	6.1	2	0	67	0	52
CAR	26	6.1	6	44	67	0	90
EAG	27	4.7	8	6	67	3	68
GIB	20	4.9	9	58	67	27	82
KJE	15	3.8	67	5	67	0	136
Treatment watersheds, post-calibration period[a]							
BAN	10	3.9	9	330	1490	0	78
CAR	26	3.9	29	440	690	37	111
EAG	27	5.3	54	190	4290	31	90
GIB	20	5.1	29	510	2280	6	100
KJE	15	6.2	68	460	1680	20	142
Control watersheds, calibration period[a]							
HEN	39	5	14	0	67	11	82
IVE	21	5	9	44	67	1	74
MUN	16	5	21	6	67	0	77
Control watersheds, post-calibration period[a]							
HEN	39	5	30	0	33	24	82
IVE	21	5	7	1290	130	26	74
MUN	16	5	23	35	39	27	77

[a] "Calibration period" ends with the onset of new road construction at each logged watershed and after 5 years at each control watershed.
[b] Based on hillslope and road erosion plot measurements (Rice, 1996); values represent total amounts displaced.
[c] Based on landslides and treethrows mapped during channel surveys; values represent amounts transported off-site.
[d] Based on application of average bank and headcut erosion rate to the areas of bank and headcut face expected to be present in the watershed (see text); values represent amounts transported beyond the plungepool lip.

for approximately 25% of the combined headcut and plungepool erosion, as plungepool depths below the residual pool surface (i.e., below the depositional lip) average about 25% of the total headcut height on 23 headcuts mapped on the YOC-ZIE tributary in 2006.

We expect retreat rates for 0.26- to 0.44-m headcuts to be lower than 4.2 cm y^{-1} and rates to be negligible for faces shorter than 0.26 m. But even at a retreat rate of 4.2 cm y^{-1}, the expected population of 0.26- to 0.44-m headcuts in control tributaries would produce no more than 4 Mg km^{-2} y^{-1} of sediment if the assumptions listed above apply also to the small headcuts.

The monitoring results indicate an average bank erosion rate of 1.6 cm y^{-1}, a value similar to rates measured on vertical faces in a grassland gully in alluvial clay soils near Berkeley, CA (2 to 4 cm y^{-1}; Reid, 1989) and on near-vertical road-cut faces in a western Washington forest (1.6 cm y^{-1}; Reid, 1981), suggesting that the measured values are reasonable for the observed conditions. To estimate total sediment input from bank erosion in control watersheds, we assume (i) the proportion of banks "susceptible to erosion" is represented as the proportion mapped during a 1995 channel survey as either undercut or vertical and composed of either alluvium or colluvium; (ii) the estimated average gully-bank erosion rate of 1.6 cm y^{-1} applies to the entire area of bank susceptible to erosion; and (iii) the measured relations between channel depth, stream power index, and drainage area defined for 3- to 30-ha watersheds apply to the full estimated drainage density of channels draining catchments of 1.9 to 30 ha.

The 1995 maps of North Fork tributaries indicate that at that time approximately half of the channel length was susceptible to erosion, with no significant difference in values between control and logged tributaries. The relation for channel depth as a function of drainage area obtained by pooling the data shown in Fig. 5 for control watersheds was then used to estimate mean depth for each channel increment throughout a hypothetical 30-ha control watershed. The above assumptions produce an estimated annual input from bank erosion of about 54 Mg km^{-2} y^{-1} in the hypothetical watershed (Table 2).

About 9 Mg km^{-2} y^{-1} of the calculated amount, or 17%, is expected to be from unmapped channels with drainage areas of 1.9 to 3 ha and so is based on extrapolation of the defined relations to smaller watersheds. A second estimate for the unmapped low-order reaches may be made by assuming that channel form near the head of a clearcut tributary is similar to that near the head of a control tributary, despite the difference in drainage areas at the channel head. If the mean bank face height of 0.5 m calculated for a mapped 40-m reach draining 1.2 to 1.3 ha of clearcut is assumed also to represent that near forested channel heads, the input by bank erosion from 1.9- to 3-ha drainage areas in control watersheds is estimated to be 12 Mg km^{-2} y^{-1}, a value similar to that estimated using morphological extrapolations.

Similar calculations employing the same estimate of the proportion of erodible bank for channels characteristic of South Fork watersheds provide an estimated input of 37 Mg km^{-2} y^{-1} from headcut erosion and 66 Mg km^{-2} y^{-1} from bank erosion in a 30-ha watershed, values 32% and 22% higher than corresponding estimates for North Fork control conditions (Table 2).

If headcut and bank retreat rates measured in North Fork control channels and South Fork channels are assumed to apply also to North Fork logged channels (exclusive of KJE), such channels would supply expected inputs of 50 Mg km^{-2} y^{-1} from headcuts and 73 Mg km^{-2} y^{-1} from banks (Table 2), values 79% and 35% higher than corresponding estimates for control conditions. The high values for headcut inputs relative to those in controls largely reflect the increased headcut face area expected in the extended low-order channel network and are offset slightly by the increase in headcut spacing downstream. Higher input rates from bank erosion reflect increases in both channel length and depth. Possible increases in headcut and bank retreat rates after logging and in percentage of the bank susceptible to erosion were not considered, so these calculations may underestimate erosion from these sources in logged watersheds.

5.2. Contribution of gully erosion to the sediment yield

To assess the importance of gully erosion relative to other sediment sources, we first compare estimates of sediment production from gullies to those from other erosion processes. Such comparisons, though instructive, do not account for differences in sediment delivery to streams and through stream channels, so we then evaluate correlations between tributary sediment yields and potential controlling influences.

5.2.1. Comparison of gully erosion rates to those of other erosion processes

The importance of gullying to sediment production can be evaluated relative to rates and patterns of erosion from other sources if total gully erosion is estimated for the length of channel present in each gaged watershed of the North Fork catchment. This calculation differs from the previous one in that channel characteristics within individual watersheds are taken into account instead of using regressed relations to construct typical conditions in a hypothetical watershed.

Sediment input from channel-bank erosion is calculated as the product of eroding bank area and average bank erosion rate (1.6 ± 1.2 cm y^{-1}) and is converted to units of mass by applying an average bulk density for the characteristic soil (1.5 Mg m^{-3}). The area of eroding banks in unmapped portions of each tributary channel network is estimated by assuming (i) channel heads are located at a drainage area of 1.9 ha for pretreatment conditions and 1.2 for logged conditions; (ii) regressions between channel depth and drainage area (Fig. 5) apply also to unmapped channels within each category of watershed; and (iii) 50% of the bank length is susceptible to erosion. Unmapped reaches (primarily first-order channels) account for 48% to 94% of the estimated channel length in individual North Fork watersheds (Table 1) and for an average of about half the estimated eroding bank area. Inputs from headcut erosion are calculated by applying an average retreat rate (4.2 ± 2.1 cm y^{-1}) to the estimated area of headcut face present in each tributary, using assumptions analogous to those employed for estimating bank erosion. Deposition on plungepool lips is then estimated as 25% of the volume eroded by headcut retreat and is subtracted from the total for each watershed.

Comparison of the estimated sediment inputs from gully erosion after logging to displacement rates estimated from road erosion plot data shows displacements from road erosion to average about 5 times greater than those accounted for by gully erosion (Table 3), and those calculated from hillslope erosion plot data to be an order of magnitude greater. Displacement from gullying, in turn, exceeds displacement from treethrows and landslides by a factor of 6.

Comparison of displacement rates to measured suspended sediment yields requires an estimate of the proportion of the total sediment load that is transported in suspension at the tributary gages. Bedload was not measured, but sediment volumes and particle sizes accumulated in the North Fork weir pond suggest that coarse sand and gravel transported as bedload contribute about 20 to 30% of the total clastic load at the North Fork weir. Comparison of the proportion of the sediment load accounted for by gravel at the weir (13%) to the proportion of gravel present in the upper 1 m of the watershed's dominant soils (25 to 50%) indicates that a high proportion of the gravel has broken down to smaller sizes before reaching the weir, suggesting that the proportion of sediment transported as bedload is likely to be substantially higher in tributaries. We here assume that 40% of the tributary sediment load is transported as bedload, so we expect total sediment loads to be about 67% higher than the suspended sediment yields noted in Table 3.

Comparison of rates of plot erosion with estimated total sediment yields demonstrates that sediment delivery rates for surface erosion sources are quite low, necessarily averaging <3% for logged watersheds. Field observations indicate that much of the sediment displaced on hillslopes is quickly redeposited on hillslopes, in low-order swales, or on valley flats and so does not contribute directly to sediment yield over the short term. Estimated sediment displacement from gully erosion is also more than sufficient to account for the total sediment loads, suggesting that deposition within channels and on valley flats may significantly influence the amount and timing of sediment exports from the tributary watersheds.

About half of the sediment from treethrows and landslides in the post-calibration period was generated during storms in HY 1995 and so would influence only a single year of the suspended sediment record for the period; most of the rest originated in 1993. Mean suspended sediment load for HY1995 in the logged watersheds was 83 Mg km^{-2}, so estimated total load averaged about 140 Mg km^{-2}. In comparison, sediment displaced by large events amounted to 63 Mg km^{-2} that year, suggesting that large events would not have provided the principal influence on sediment yield even during a year with a high incidence of landsliding.

In addition, examination of annual yields at tributary gaging stations indicates that ranks in suspended sediment yield were relatively consistent from year to year between 1991 and 1995 (Fig. 8), suggesting that yields during this period were largely controlled by chronic sediment sources rather than by discrete, sediment-producing events such as landslides. The highest rankings for tributaries were not associated with years in which significant landslides were observed in those tributaries.

The relative importance of landslides is likely to be greater over the long term because of the rare occurrence of very large slides. Between 1986 and 2006, for example, total sediment displacement from landslides and near-stream treethrows throughout the North Fork watershed averaged over 200 Mg km^{-2} y^{-1}, and the two largest slides were responsible for about 50% of the displacement. Had the period of extensive suspended sediment monitoring (1986–1995) included one of these major landslides, landsliding would have undoubtedly influenced short-term sediment yields; but results here suggest that influences from the landslides and treethrows mapped during the study period are not expressed as acute short-term increases in yield. Both of the largest slides occurred on logged slopes and triggered debris flows, resulting in considerable volumes of deposition within and adjacent to downstream channels. Such deposits are likely to be remobilized later by channel incision, thus eventually contributing additional suspended sediment through gully erosion.

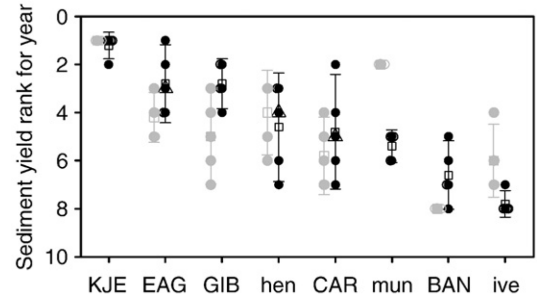

Fig. 8. Relative rankings in suspended sediment yield at tributary gages for HY1986–1990 (gray symbols) and HY1991–1995 (black). Open squares indicate mean rank for the period, and data points for years with significant landslides within individual watersheds are enclosed in triangles. Upper-case gage names indicate logged tributaries.

5.2.2. Correlation analysis

The relative importance of various sediment sources can be further evaluated by analyzing correlations between sediment displacement rates and suspended sediment loads in the gaged watersheds to identify the combination of source inputs that best explains the observed distribution of yields. Irrespective of sediment delivery ratios and grain size distributions, the relative distribution of suspended sediment yields among watersheds is expected to reflect the relative distributions of sediment displacements from the processes that most strongly influence sediment yields. For this analysis, accuracy of the estimated sediment inputs is not as important as the relative values between watersheds within a source type.

We carried out a step-wise multiple regression of mean suspended sediment yields (*SSY*, Mg km^{-2} y^{-1}) from calibration and treatment periods in each tributary watershed against estimated erosion from gullies (*G*, Mg km^{-2} y^{-1}), large events, road plot erosion, hillslope plot erosion (P_h, Mg km^{-2} y^{-1}), and watershed area to evaluate the relative influence of these factors on the distribution of suspended sediment yields. The resulting model (Fig. 9) employs only two variables:

$$SSY = -41.5 + 0.702\,G + 0.0050\,P_h \quad \text{adjusted}\,R^2 = 0.77 \tag{1}$$

The relation is highly significant at the 0.05 level, with gully erosion by itself explaining 73% of the variance; the hillslope term is only marginally significant ($p = 0.05$). Results suggest that gullying and associated processes in logged watersheds contribute about three to seven times as much sediment to the sediment yield as processes assessed by hillslope erosion plots. In forested watersheds the difference is greater, with gullying responsible for about 50 to 200 times as much as hillslope erosion. Delivery of hillslope sediment to streams depends in part on the extent of the channel network, so the

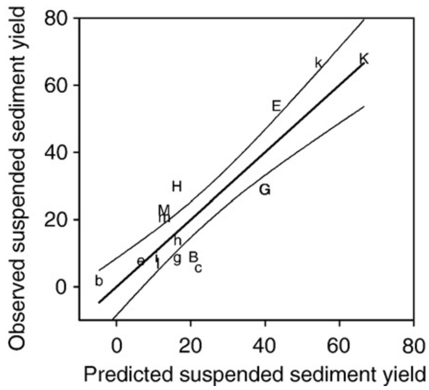

Fig. 9. Observed suspended sediment yields (Mg km^{-2} y^{-1}) versus those predicted using Eq. (1). Lower case initials represent data for the calibration period in each watershed. Points C and G are superimposed.

apparently overwhelming importance of gully erosion may actually reflect both in-channel erosion and the increased efficiency of hillslope sediment delivery due to network expansion after logging.

If bedload is assumed to account for 40% of the total sediment yields at the tributary gages, about half the estimated sediment eroded from banks and headcuts is not delivered to the downstream gage, suggesting that either the rate of gully erosion is overestimated or that significant deposition is occurring within channels and on floodplains. An average channel aggradation rate of 2 mm y^{-1} would account for the undelivered sediment, and if aggradation is indeed occurring at this rate it should become evident from cross-section measurements in the near future. However, given the uncertainties associated with the rate calculations, we expect that imprecision in estimated rates is likely to account for most of the discrepancy.

5.3. Mechanisms of influence from logging

Results of the study suggest that clearcut logging at Caspar Creek caused a significant increase in gully-related sediment inputs (Table 2). Such increases might reflect either increased runoff associated with logging or direct disturbance of low-order channels during cable-yarding operations. Several kinds of information suggest that hydrologic change is likely to be the dominant influence in the present case.

5.3.1. Evidence from network extent

Field measurements suggest that channel heads migrated upslope after logging (Fig. 7, Table 2) and that the stream power index associated with the channel head locations is significantly lower in logged watersheds than in controls. However, the utility of the stream power index (calculated as drainage area × gradient) as a measure of actual stream power relies on the assumption that drainage area is a valid index for relevant discharges. Once a site is logged, the relation between drainage area and characteristic discharges changes.

In North Fork watersheds, the mean peakflow for flows with recurrence intervals longer than 0.15 y increased by about 60% in the 2 years following logging (Reid and Lewis, 2007), with increases approaching an asymptote of 34% for flows occurring fewer than 3 times a year. Effective maximum stream power per unit drainage area during storms thus averaged 60% greater after logging, so a post-logging stream power index of 0.34 ha is equivalent to a pre-logging index of 0.54 ha. If this hydrologic shift is accounted for, the recalculated index at the channel head is not significantly different at the 0.05 level between logged and control watersheds (Fig. 7).

This finding may indicate either that the hydrologic change is sufficient to explain the shift in channel-head location or that the hydrologic change prevented healing of mechanically disrupted sites over the period following yarding. Low-order tributaries are most susceptible to influences from direct disturbance, and the prevalence of subsurface soil pipes in headwater channels would make these sites particularly sensitive to mechanical disruption. However, changes in channel characteristics in logged watersheds along the 65% of the mapped channel length protected by buffer strips could not be explained by direct disruption because disturbance within the buffers is minimal.

5.3.2. Evidence from nested gages

If hydrologic change is an important influence on in-channel erosion after logging, channels downstream of logged watersheds should show increases in sediment yield that cannot be explained simply by changes in sediment input from upstream.

A pair of nested stream gages provides the data needed to assess downstream variations in sediment yield in a gullied tributary. Gage DOL (with a 77-ha catchment) lies downstream of gage EAG (27 ha) in the North Fork watershed. The catchment above the EAG gage was logged in 1991, and hillslopes abut most of the channel length in the EAG catchment. In contrast, the catchment between the EAG and DOL gages has not been logged since 1904, and valley-fill terraces buffer much of the channel from hillslope inputs. Several small tributaries enter this reach, but alluvial fans at most tributary mouths appear to trap much of their coarse sediment load and some fine sediment. Visible sources of sediment within the reach include incised stream banks, headcuts, and near-stream treethrows.

Suspended sediment loads measured during storms at the EAG gage were subtracted from corresponding loads at the DOL gage to estimate the load derived from the unlogged portion of the watershed. Loads for the pre-logging period in both portions of the watershed were then regressed against the mean of loads at control watersheds HEN and IVE to allow prediction of expected loads. The ratios of observed to expected loads from the unlogged portion of the watershed show a response similar in initial timing and magnitude to that from the logged portion of the watershed (Fig. 10), though the downstream portion reattained pre-logging values more quickly than the logged portion. Sediment input increased again in the DOL reach after regrowth in the EAG watershed was thinned in 2001. The sediment record thus indicates that upstream logging influenced sediment production in unlogged portions of the downstream watershed where there was no direct disturbance, suggesting that hydrologic change may indeed have been influential.

However, it is also possible that a portion of the sediment appearing to have originated within the DOL reach may represent

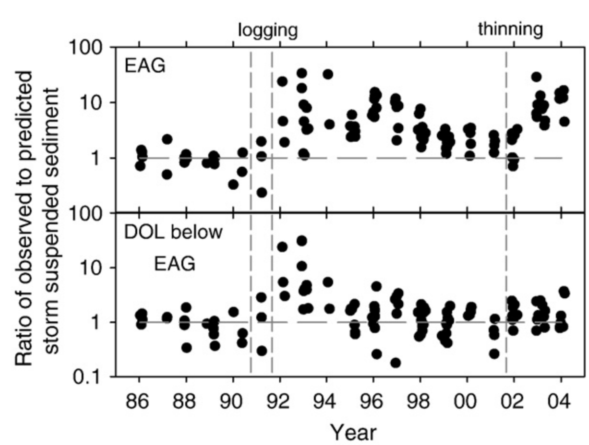

Fig. 10. Deviations from expected suspended sediment load in the clearcut EAG watershed and in the unlogged portion of the DOL watershed downstream of the EAG gage. Values are corrected for bias from back-transformation from logarithms (Baskerville, 1972).

breakdown of bedload into suspendible sizes: bedload originating in EAG would not be included as part of the EAG suspended load, but if it then becomes suspendible downstream it would be recorded as suspended load at the DOL gage. The potential magnitude of this effect can be estimated if bedload is assumed to represent 40% of the total sediment load at EAG. DOL produced 197 Mg of excess suspended sediment between 1991 and 1995, compared to 38 Mg from EAG, indicating that breakdown could explain no more than 13% of the post-logging sediment increase from DOL even if all EAG bedload were transformed to suspended load within the DOL channel. In actuality, much of the EAG bedload is trapped on a minimally channeled fan immediately downstream of the gaging station, so breakdown is likely to explain substantially less than 13% of the increase.

At a larger scale, Lewis et al. (2001) evaluated post-logging changes in suspended sediment yield across the full suite of nested North Fork stream gages and found that observed changes in suspended sediment yield after logging were more closely correlated with changes in flow than with other indices of management activity levels.

5.3.3. Morphological changes associated with headcut migration

Results of morphological comparisons for logged and control tributaries also are consistent with a situation in which channel morphology has been influenced by increased flows after logging. Contrasts in morphology between logged and control watersheds are revealed not so much by changes in average channel dimensions as by changes in the relations between channel dimensions and controlling variables such as stream power and drainage area (Fig. 5), and by increased spacing between headcuts after logging (Fig. 4).

The contrasting patterns may reflect an increase in the frequency with which headcuts are destabilized after logging. Newly mobilized headcuts can retreat rapidly until they encounter an upstream plungepool or a hardened lip supporting another headcut. Two discontinuous gullies will then have coalesced, thereby decreasing the number of headcuts present and increasing mean headcut spacing while not strongly affecting headcut height. Mean channel cross-sectional area would increase in areas where gullies coalesce. Reaches experiencing large changes in any particular year are likely to be distributed randomly, as the ability for a headcut to retreat rapidly is strongly influenced by the condition of elements armoring its lip. Overall patterns of distribution for morphological characteristics are thus likely to become less regular as the system continues to adjust to the sequence of changing hydrologic conditions.

Increased coalescence of headcuts in logged tributaries is also consistent with observed differences in the relative importance of stream power and watershed area as predictors of morphological characteristics in control watersheds and in the pervasively gullied watershed KJE (Fig. 5). In general, where gullies are present as a series of headcuts, headcut location–and the resulting distribution of incised reaches–might strongly reflect local conditions. For a channel segment with uniform discharge, incision is expected to persist along the steeper portions (high stream power), while low-gradient portions (low stream power) may aggrade. In contrast, where gullies have coalesced, incised reaches also span low-gradient reaches between initial headcut locations. Because the fine-scale patterns of incision and deposition in discontinuous gullies are superimposed on the broader pattern of a general increase in channel size downstream, which persists when gullies coalesce, stream power would then become a less efficient predictor of attributes such as width, depth, and cross-sectional area than would drainage area alone.

Morphological characteristics associated with reaches having low headcut frequencies are expected to diverge between logged and control watersheds as logged channels adjust to altered conditions. If low frequencies in logged reaches indicate coalescence of headcuts rather than absence of incision, mean channel depths in reaches with few headcuts should be greater in logged watersheds than in control watersheds, and this is indeed the case. In channel segments where headcut frequency is less than about 10/100 m of channel, mean channel depth is significantly greater in logged watersheds (1.6 ± 0.4 m) than in control watersheds (0.7 ± 0.2 m, Fig. 11). In the South Fork watersheds, the distribution of channel depths as a function of headcut spacing is most similar to that in North Fork control watersheds.

5.4. Contrasts between North Fork and South Fork channels

The intermediate position of South Fork channel morphological relations relative to those in North Fork control and clearcut watersheds (Fig. 6) may in part reflect ongoing recovery from second-cycle logging effects in the South Fork. The South Fork was logged 28 to 30 years before the gully survey, while North Fork watersheds had been logged only 10 to 12 years earlier. Differences in silvicultural strategy and yarding techniques would also contribute to differing results. The selective logging employed in the South Fork resulted in less hydrologic change from altered vegetation than in the clearcut North Fork watersheds, but the use of tractors for yarding produced widespread compaction that continues to generate overland flow at some sites. In addition, South Fork logs were skidded along some low-order channels, directly disrupting the channels and likely producing a very different distribution of channel forms immediately after logging than was present after North Fork logging. Also in contrast to the North Fork, South Fork roads and landings were located mid-slope and in riparian zones, strongly

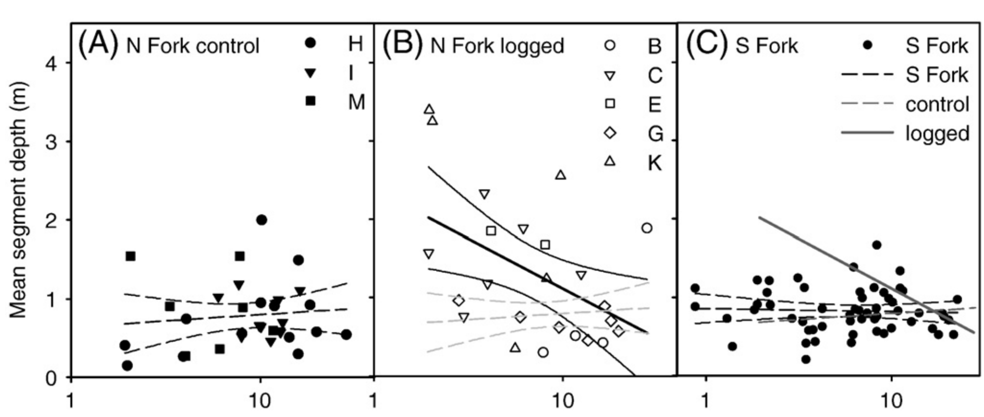

Fig. 11. Mean depth and headcut frequency in 50-m channel segments of (A) North Fork control, (B) North Fork logged, and (C) South Fork tributaries. Relations significant at the 0.05 level are depicted by solid lines.

increasing the potential for channel disruption by road drainage and mechanical disturbance.

5.5. Implications for forest management

Efforts to prevent and mitigate logging-related erosion in rain-dominated watersheds of the Pacific Northwest have generally relied on the use of buffer strips and on reduction of road-related erosion. Road erosion was found not to be of major consequence at North Fork Caspar Creek (Lewis et al., 2001), possibly reflecting drainage control efforts, road closures following logging, and pervasive water-barring of abandoned roads. Most North Fork roads and log landings are located near ridge tops, further reducing their potential for contributing sediment directly to channels. Robust buffer strips were incorporated into the logging plan, providing extensive filter strips below upland sediment sources and preventing direct disturbance to a significant portion of the stream network. Despite these measures, suspended sediment yields increased significantly after logging, and much of the increase appears to originate from gully-related processes that are not amenable to mitigation either through road improvements or buffer strips. If increased runoff after logging generates sediment from within downstream channels, control of excess sediment from this source would be possible only through management of the level of hydrologic change induced by logging, and this would require either management of the rate of logging within a watershed or modification of the silvicultural strategy used.

Logging prescriptions generally consider only the distribution of channel types present at the time that plans are developed and so do not reflect the possibility that the channel network may expand after logging. The apparent 28% increase in drainage density after logging at Caspar Creek would strongly increase the connectivity between hillslope sediment sources and the downstream channel network. Plans to maintain a prescribed distance between ground-disturbing activities and stream channels are defeated if channel networks expand into the disturbed sites after logging.

Logging plans on lands administered by US Federal agencies or regulated by California State agencies are required to include an evaluation of potential cumulative and indirect impacts of the planned logging, but considerable uncertainty and controversy have at times surrounded the definition of what constitutes an adequate impact analysis. Observation of the Caspar Creek gullies suggests that future analyses might usefully consider the possible influence of logging-related hydrologic changes on downstream channel morphology and sediment inputs.

Interest is growing in the use of indirect methods for inferring long-term erosion rates to allow comparison to management-related sediment inputs. Several studies have evaluated concentrations of cosmogenic ^{10}Be in soils and sediment to estimate long-term input rates (e.g., Kirchner et al., 2001). In the case of Caspar Creek, Ferrier et al. (2005) used results of such a study to conclude that recent erosion rates evaluated from monitoring data at Caspar Creek are lower than rates characteristic of the pre-logging period. Such conclusions rest heavily on the assumption that the distribution of sediment sources that produced the sampled sediment is typical of the distribution present over the period for which long-term rates are to be inferred. However, examination of the Caspar Creek tributaries indicates that gullying is now pervasive, that it probably initiated with or was greatly accelerated by first-cycle logging, and that many of the gullies excavate cosmogenically “pristine” sediment sources such as buried saprolite and bedrock. Under these conditions, samples obtained from in-channel sediments will contain lower ^{10}Be concentrations than would be expected from sediment exported before gully initiation, and estimated “long-term” erosion rates may instead disproportionately reflect accelerated erosion resulting from first-cycle logging.

6. Conclusions

Results of the Caspar Creek study suggest that erosion along incised channels is an important source of sediment in tributary watersheds. Gullying in the area appears to have expanded with first-cycle logging of the late 1800s. Channels had not yet recovered from the earlier impacts at the onset of second-cycle logging nearly 100 years later, and increased runoff resulting from second-cycle logging accelerated erosion within the still-incised channels. Recently logged watersheds show a higher drainage density than controls, with the extent of the increase similar to that expected on the basis of the observed change in runoff.

Because an appreciable portion of the increased sediment input at Caspar Creek is associated with hydrologic changes caused by logging and because a significant portion of the excess sediment is generated along channels in and downstream of the logged areas, the strategies most often used in the region to reduce sediment inputs from logging–control of road-related erosion and establishment of riparian buffer strips–are not effective for reducing an important component of the logging-related sediment input at Caspar Creek. In addition, efforts to reduce impacts from surface erosion by ensuring that soil-disturbing activities are not carried out near streams would need to take into account the potential for upslope expansion of the channel network after logging.

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