Effectiveness of Road Restoration in Reducing Sediment Loads

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Final Report

Summary

This report summarizes findings from a field evaluation of post-treatment erosion on decommissioned roads. Erosion control treatments were applied to abandoned logging roads in Redwood National and State Parks, north coastal California, with the goal of reducing road-related sediment input to streams and restoring natural hydrologic patterns on the landscape. Treatment of stream crossings involved excavating culverts and associated road fill and reshaping streambanks. Road reaches were treated with a variety of techniques, which included decompacting the road bench, placing unstable road fill in more stable locations, and reestablishing natural drainage patterns. Following treatment and a 12-year return period storm in 1997, 61 km of treated roads were inventoried, encompassing about 300 road reaches and 200 stream crossings. Several treatment sites showed evidence of mass movement failures, gullying, bank erosion and channel incision: 14% of the road reaches and 33% of the excavated stream crossings produced more than 35 m^3 of sediment (50 yd^3). Post-treatment erosion on road reaches was related to method of treatment, hillslope position (upper, mid-slope or lower), and date of treatment. During the period following treatment, treated roads in upper and mid-slope positions contributed an average of 10 and 135 m^3 of sediment/kilometer of treated roads (20 and 285 yd^3/mile), respectively. Treated roads on lower hillslopes contributed 550 m^3 of sediment per km of road (1160 yd^3/mile) into stream channels. On gentle, convex upper hillslopes, minimal treatment (rip and drain and partial outslope) were effective in stabilizing the roads. On mid-slope roads, more intensive treatment was needed. Road reaches in steep, lower hillslope positions had the highest erosion rate in this study, no

matter what type of treatment method was used. This fact points to the need to either avoid construction or improve construction techniques in these geomorphically sensitive locations, because mitigation through road removal is not totally effective at these sites. Erosion inventories in adjacent catchments indicate that untreated roads can produce 1500 to 4700 m^3 of sediment/km. Thus, although road removal treatments do not completely solve the erosional problems associated with unpaved roads, they do substantially reduce sediment yields from abandoned logging roads.

Introduction

Forest roads are significant sources of sediment, as identified by many researchers (Janda and others, 1975; Kelsey and others, 1981; Best and others, 1995). Abandoned and unmaintained roads once used for timber harvest are common across the steep, forested landscape of southwest Canada and the Pacific Northwest of the United States. The construction of haul roads across steep slopes frequently results in massive landslides and extensive gullying that contribute sediment directly into perennial and intermittent stream channels. Sidecast material from road construction can mobilize when it becomes saturated, or can gully if road runoff is diverted onto previously unchanneled slopes.

The installation of drainage structures such as culverts disrupts natural drainage patterns. Stream crossings fail when culverts plug with sediment or wood, or are too small to convey storm discharge, and the road fill at the stream crossing consequently erodes. Drainage structures can divert streams out of their natural course when the structures fail to function properly. For example, if a culvert plugs and the road slopes away from the culvert inlet, runoff is diverted from the channel and may flow down the road onto an unchanneled hillslope. These diversions frequently result in further gullying or road fill failures. Road cuts can intercept groundwater and increase the amount of surface runoff. As a result of hydrologic rerouting, some streams receive an increase in discharge, and the channels enlarge through bank erosion and incision. In addition, widespread surface runoff from the road bench and cutbanks flows into inboard ditches, which commonly deliver sediment to channels.

In response to the erosional threat posed by unpaved forest roads, many agencies (the United States National Park Service , U.S. Forest Service, California Department of Fish and Game, and others) are funding programs to upgrade existing roads and to remove roads that are no longer needed for the transportation network. In 1978, the National Park Service initiated one of the earliest and most extensive of such programs at Redwood National Park in north coastal California. At that time, Redwood National Park was expanded to include 15,000 ha of recently logged lands. Most of the redwood forest on this land had been tractor logged, which resulted in an extensive network of unpaved haul roads and tractor trails (skid roads). The expanded park included more than 650 km of abandoned haul roads and 4800 km of smaller skid trails. Due to a concern regarding downstream impacts of roads on streamside redwood forests and salmon-bearing rivers, the U.S. National Park Service initiated a watershed rehabilitation program to reduce the sediment production from these abandoned roads. The purpose of the program, as stated in Public Law 95-250, was to reduce human-induced erosion within Redwood National Park and encourage the return of natural patterns of vegetation.

The main focus of the watershed rehabilitation program has been to reduce sediment delivery from abandoned haul roads and restore natural drainage patterns. Typical treatments include decompacting the road surface, removing drainage structures (primarily culverts), excavating road fill from stream channels and exhuming the original streambed and streambanks, excavating unstable sidecast fill from the outside edge of road benches or landings, filling in or draining the inboard ditch, and mulching and replanting the sites. Since 1978 there has been an evolution of road rehabilitation techniques, which will be discussed in more detail below. About 300 km of abandoned logging roads were treated between 1978 and 1996 (Figure 1).

The rehabilitation program at Redwood National Park operated for many years under benign weather conditions, and between 1978 and 1996 Redwood Creek had no floods of greater than a five-year recurrence interval. In 1997, the treated roads received their first 'test' in the form of a storm with 12-year recurrence interval. Although storm damage reports documented many landslides and culvert failures on untreated roads (Redwood National Park, unpublished reports), the effect of the storm on treated roads was not known. An evaluation of treated roads was initiated to assess the success of the park's rehabilitation program in meeting its goal of sediment reduction from treated roads following a large storm.

The purpose of this paper is to evaluate the erosion and sediment delivery from treated roads measured after the 1997 storm. The format of the study is retrospective rather than experimental because the road treatments from 1978 to 1996 were not applied in a systematic manner. Several questions are posed in the present assessment: Is

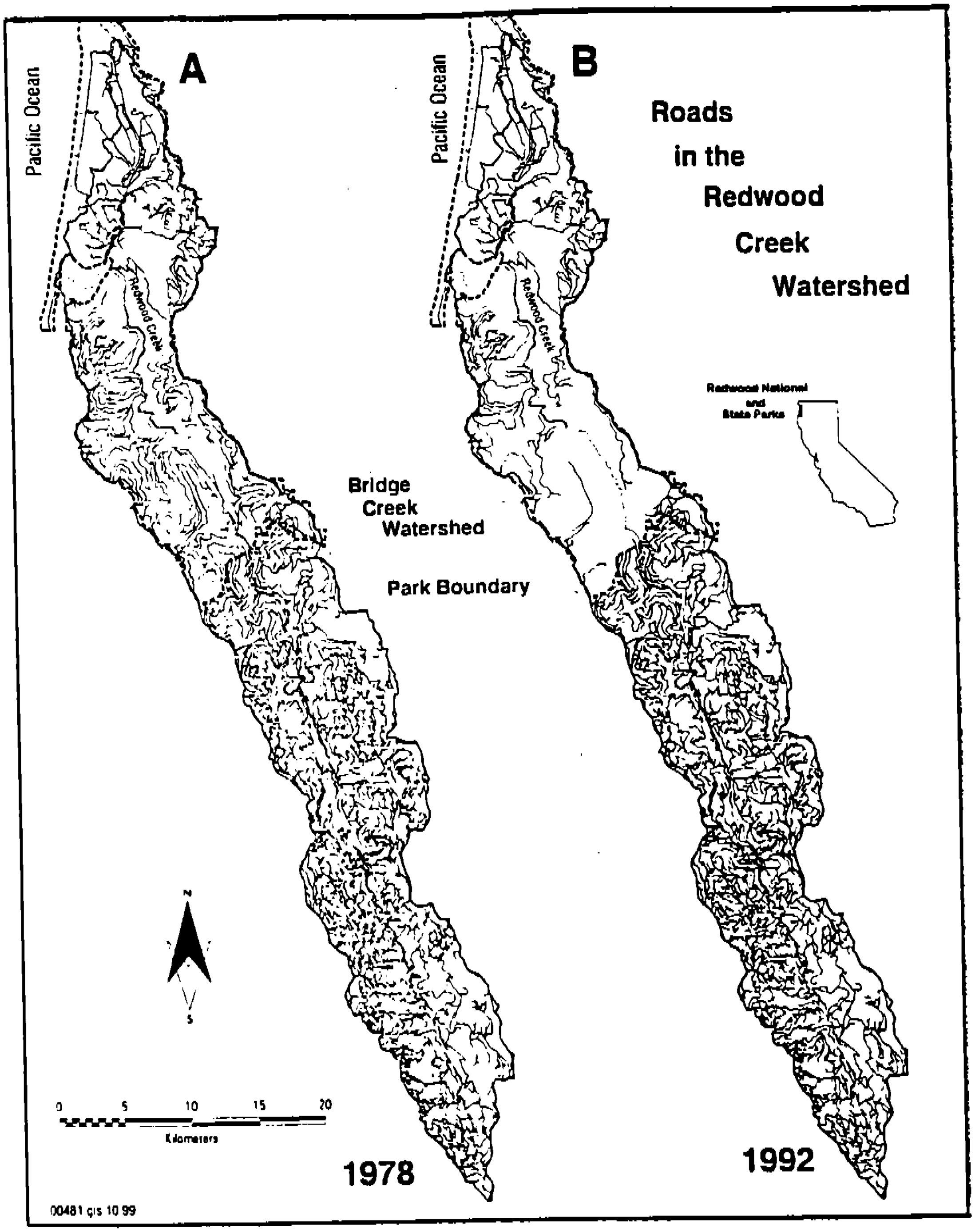


Figure 1: Location map of the Redwood Creek basin showing the distribution of roads in 1978 and 1992. Since 1978, about 300 km of road have been removed from the downstream third of the basin, which is managed by federal and state parks. The upstream two-thirds of the basin is privately owned, and timber harvest is the primary land use.

post-treatment erosion from removed roads related to geomorphic characteristics? Specifically, did treated roads respond differently as a function of their hillslope position? Were roads in areas of convergent groundwater (concave slopes) more likely to fail? Did the type of underlying bedrock influence post-treatment erosion? Did the effectiveness of different road treatment methods in terms of reducing sediment yields vary significantly? Because the level of revegetation of treated sites increases with time, was post-treatment erosion related to time since rehabilitation? How much revegetation occurred on the sites, and what was the species composition of the regrowth? Was post-treatment stream channel adjustment related to stream power? Were rolling dips effective on roads that were to remain part of the transportation network? From a basin-wide perspective, have road rehabilitation treatments significantly reduced sediment delivery from forest roads into streams?

Previous Studies

Many researchers have documented the effects of timber harvest and associated road construction in the Redwood Creek catchment. Janda and others (1975) described watershed conditions in the Redwood Creek catchment, including the extent of timber harvest and some of its effects on the landscape. Their initial work spawned a series of more detailed studies of specific erosional processes. Ground surface lowering due to overland flow on forested slopes and logged sandstone slopes was minor compared to modern sediment yields, but sheetwash on tractor-logged schist slopes can be a significant sediment source (Marron and others; 1995). Weaver and others (1995) found that gullying was a major erosion process on roaded prairies and logged lands in the Redwood Creek basin, and most of the gullies originated on unpaved logging roads. A sediment budget for Garrett Creek, a tributary to Redwood Creek, showed that road construction and logging produced almost all significant sources of hillslope erosion (Best and others, 1995). Landslides associated with roads and recently logged hillslopes accounted for nearly 80 percent of total landslide erosion measured in the Redwood Creek catchment (Pitlick, 1995). Finally, Nolan and Janda (1995) reported that synoptically measured values of suspended-sediment discharge were roughly 10 times greater from harvested terrain than from unharvested terrain.

Although increased erosion rates and sediment yields following road construction and logging have been well documented in the Redwood Creek catchment, few studies address the reduction of erosion rates following road removal. Klein (1987) measured channel adjustments during the first year following excavations of 24 stream crossings in Redwood National Park. Following a five-year return interval flood, crossings eroded an average of 0.8 m^3/m of crossing length. Post-treatment erosion was most strongly related to stream power and inversely related to the percent of coarse material in stream banks and large wood in the channel. Luce (1997) found that road ripping (decompacting the road bench) was effective in increasing the hydraulic conductivities of road surfaces, but did not restore the conductivities to those of a forested slope. Bloom (1998) contrasted the erosion derived from treated and untreated road segments in Redwood National Park following the 1997 storm, and reported that storm-related erosion on untreated roads was four times greater than on treated roads, and that erosion was related to hillslope position and proximity to fault zones.

Field Area

The Redwood Creek catchment, located in the northern Coast Ranges of California, USA, is underlain by rocks of the Franciscan Assemblage, mostly sandstones, mudstones and schist. The Grogan Fault bisects the elongate catchment and juxtaposes sedimentary and metamorphic rocks. Redwood Creek follows the trace of the Grogan Fault for much of its length, and several tributaries also follow a presumed fault (the Bridge Creek Lineament) (Harden and others, 1981). Forested blockslides are more common on schist terrain (Sonnevil and others, 1987), whereas earthflows are more common on the sandstone terrain. Redwood Creek drains an area of 720 km^2 and the basin receives an average of 2000 mm of precipitation annually, most of which falls as rain between October and March.

Total basin relief is 1615 m and the average hillslope gradient is 26%. Typical hillslope profiles consist of broad, convex ridges with steeper streamside slopes, where streamside landslides are common. Locally, a break in slope separates the more gentle upper hillslopes and steeper (>65%) streamside hillslopes, which is called an inner gorge (Kelsey, 1988). Floodplain development is limited in the Redwood Creek catchment, and the streams considered in this study are highly constrained (valley width is less than two channel widths). None of the roads included in this study was located on a floodplain or terrace. Stream gradients of excavated stream crossings averaged 10 to 25%.

Prior to timber harvest, a conifer forest dominated by coastal redwood (*Sequoia sempervirens)* and Douglas fir *(Pseudostuga menziesii)* covered most of the catchment, although scattered grasslands and oak-woodlands lined the eastern ridgetops. By 1997, 80 percent of the original coniferous forest had been logged, and parklands encompass the remaining old-growth forests. The primary silvicultural method was clearcut logging and tractor yarding, which resulted in extensive ground disturbance and large areas of bare soil. Widespread construction of haul roads and smaller skid roads accompanied the timber harvest activities.

Description of Road Treatments

The first step in treating forest roads was to map the geomorphic and hydrologic features of the road and adjacent hillslopes. Erosion features, drainage structures, the stream network, and the location of all roads, skid trails, seeps, and springs were identified on enlarged aerial photographs at a scale of 1:1200. Following the mapping phase, road removal treatments were designed and implemented. In the early 1980's, road treatment work focused on removing culverts and pulling back road fill from streambanks (Figure 2a-d). In some cases, newly excavated stream channels were protected with check dams or large rocks (Figure 2b). The crossing excavations surveyed in this study varied from 100 to 7500 m^3 in volume, and averaged about 1000 m^3. Figure 2 shows an averaged sized crossing, whereas Figure 3 is an example of a small crossing excavation.

On road reaches between stream crossings, a variety of techniques were used, which varied in the amount of earth moving involved (Figure 4a-e). Treatments in the

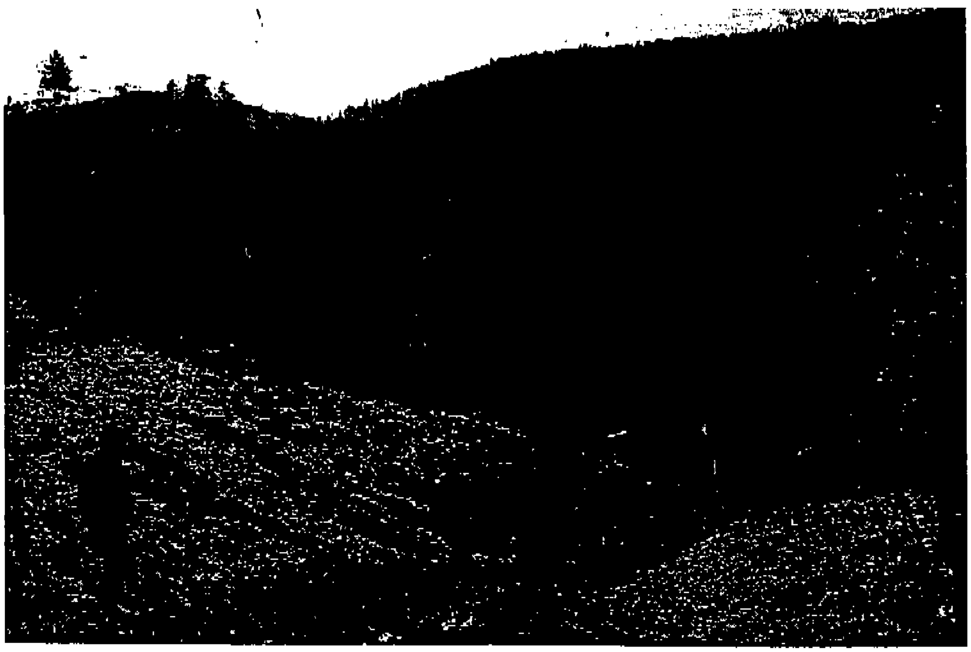


Figure 3: Another example of an excavated crossing. In this case, the stream channel is not as incised as the one in Figure 2, so the streambanks are not as steep or high.

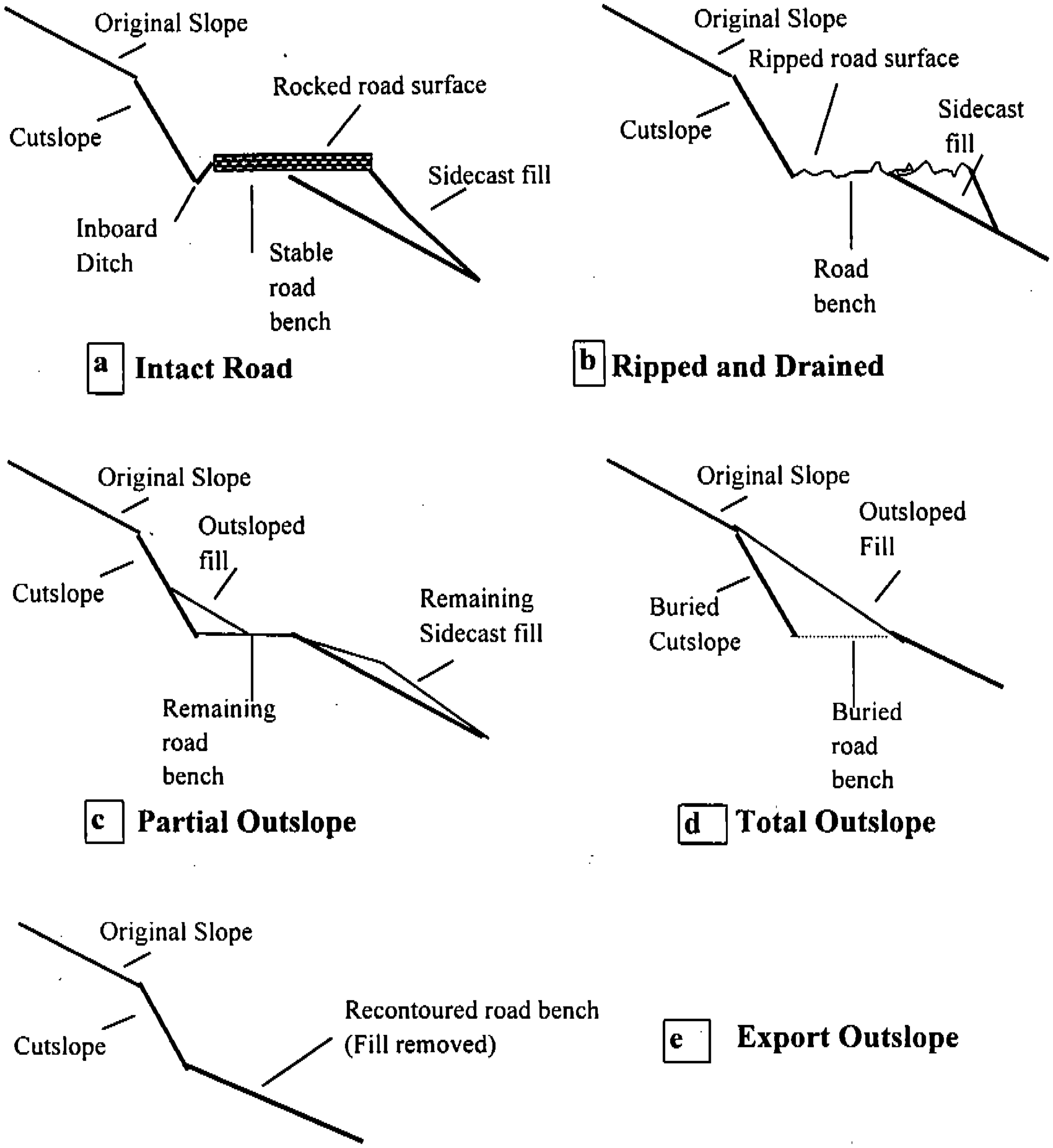


Figure 4: Schematic diagram showing the 'anatomy' of a road bench and various road treatment techniques. a) Intact road bench with rocked surface and inboard ditch. b) The road is ripped and drained, so the rocked surface is disaggregated and the function of the inboard ditch is eliminated. c) Partial outslope, in which the steepest sidecast fill is placed at the toe of the cutbank. d) Total outslope, in which all sidecast fill is placed at the toe of the cutbank. e) Export outslope, where all the sidecast fill is removed from the road bench entirely.

early 1980's decompacted the road surface and constructed deep drains perpendicular to the road alignment to dewater the inboard ditch (a technique referred to as 'ripped and drained'). Typically, 200 to 500 m^3 of road fill was excavated for every kilometer of road treated (420 to 1050 yd^3/mile) with this method. This approach is the least intensive treatment (Figure 4b). Following this treatment, the roads were mulched, primarily with straw, and replanted with native vegetation (Figure 5a and b).

As the program progressed, park geologists began to use more intensive treatment methods, which included partially outsloping the road surface by excavating fill from the outboard edge of the road and placing the material in the inboard ditch at the base of the cutbank (Figure 4c and Figure 6). This technique required more earth moving (1000 to 2000 m^3/km of treated road, or 2000 to 4000 yd^3/mile). By the 1990's, geologists commonly prescribed total outsloping and complete recontouring of the road bench, in which the outside edge of the road is excavated down to original ground and excavated fill is placed on the cutbank and shaped to follow the contours of the original topography. Stream channels were excavated to the original channel bed elevation and streambanks were extensively reshaped (Figure 4d and Figure 7). Total outsloping involved moving an average of 6000 m^3/km of treated road (13,000 yd^3/mile). Artificial channel armoring was seldom used in this phase, but trees felled during road treatment were later placed in the stream channels and on the treated road surface (Figure 8). On some road segments, excavated road fill was removed from the road bench and transported to a more stable location. This treatment was termed 'export outslope' (Figure 4e), and the locations where the road spoils were placed were called fill sites. Export outsloping removed the entire road prism, and involved the greatest amount of earth moving (15,000 to

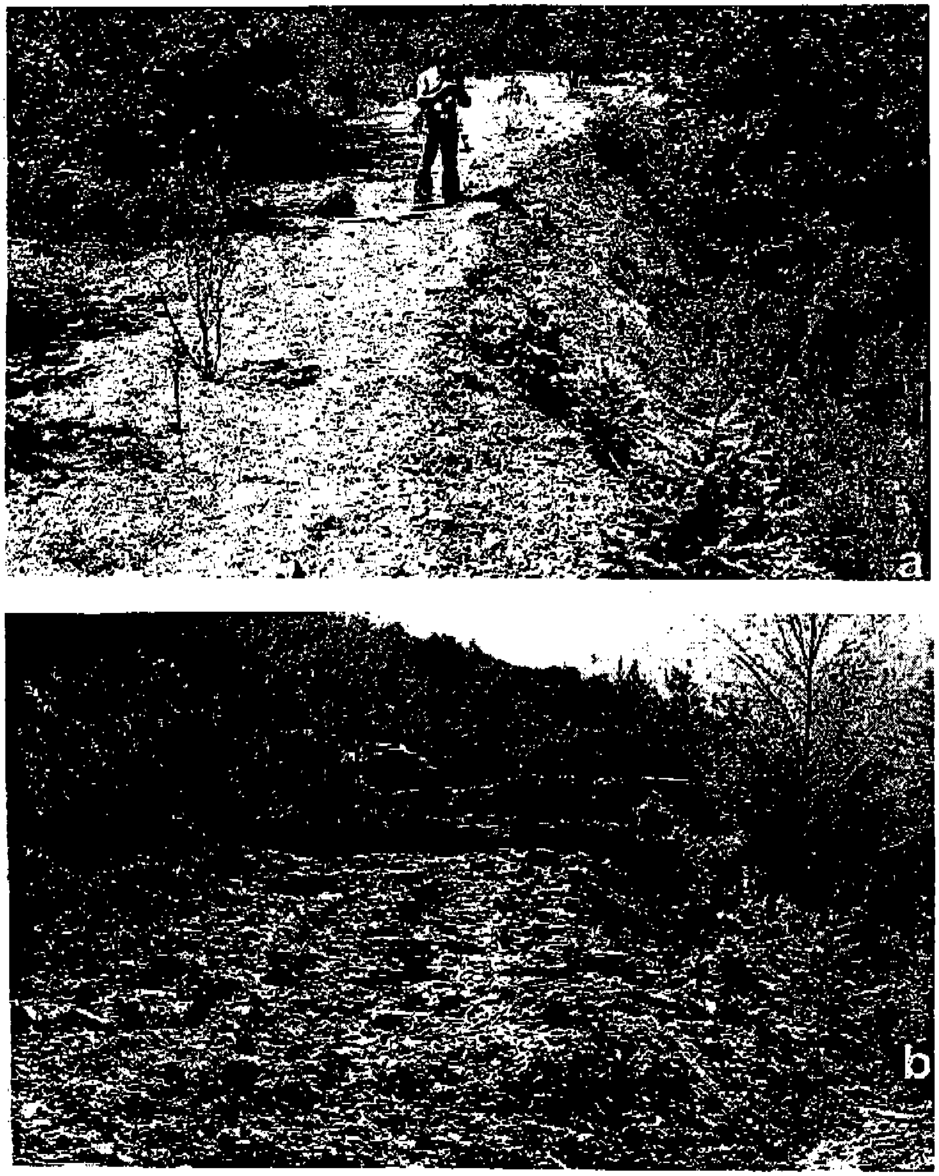


Figure 5. An example of the least intensive road rehabilitation technique. a) Abandoned logging road before treatment. b) The road surface is decompacted, and ditches are constructed perpendicular to the road alignment to drain the road. The road bench and road fill remain in place.

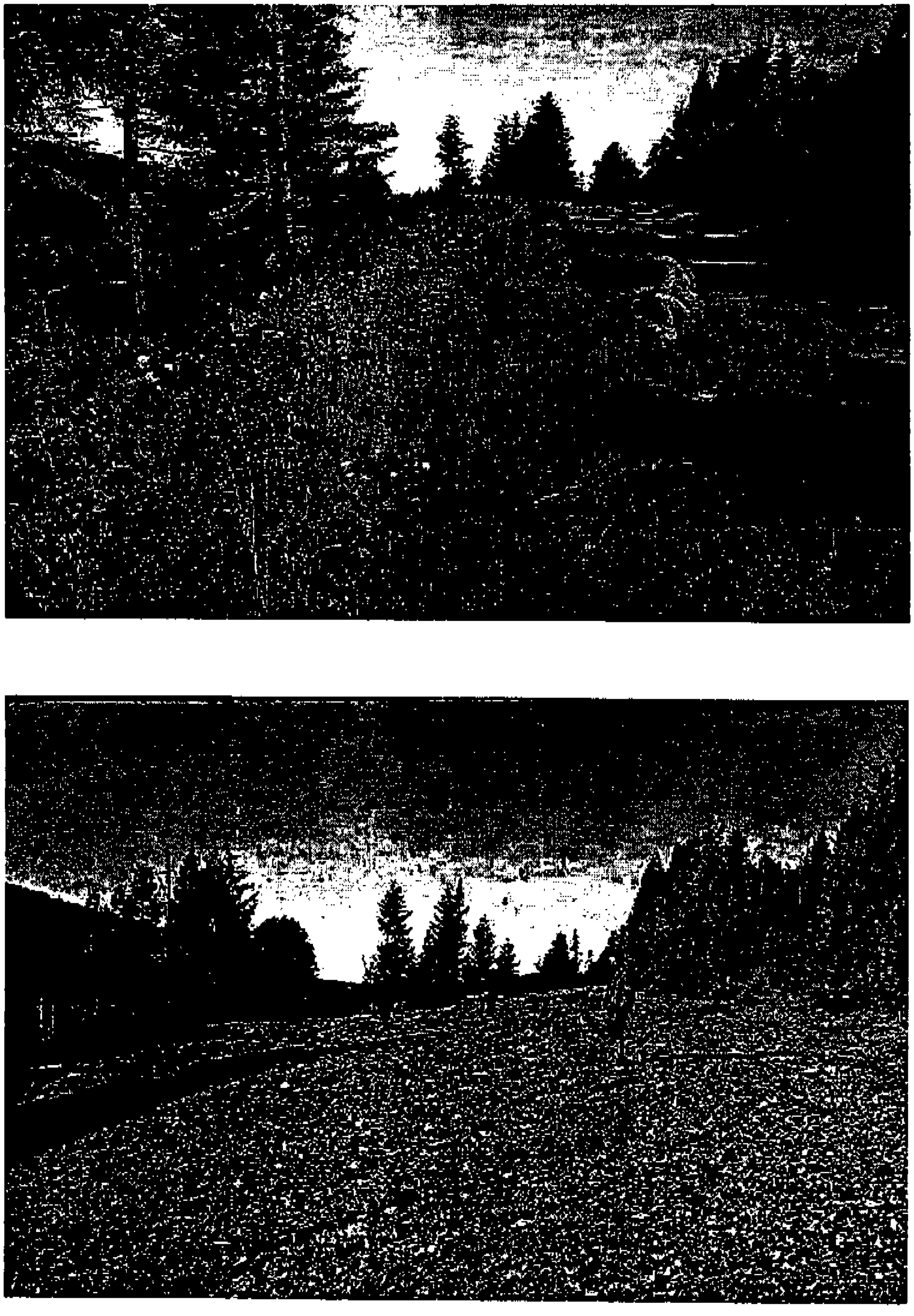
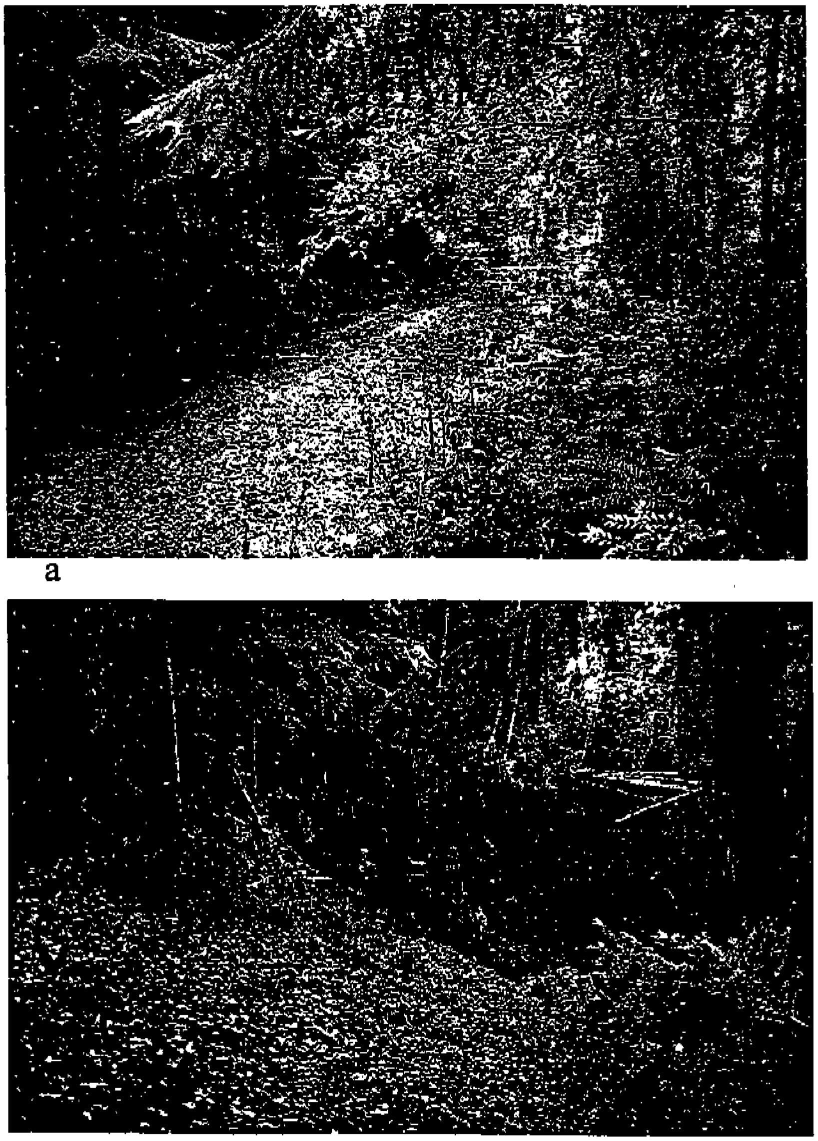


Figure 6. An example of partial outsloping a road bench.



a

b

Figure 7: An example of the most intensive road rehabilitation technique. a) Abandoned logging road before treatment. b) The road bench is obliterated and the hillslope recontoured (total outsloping of the road bench, and total excavation of the stream channel). Note person for scale next to a stump that was exhumed during channel excavation.

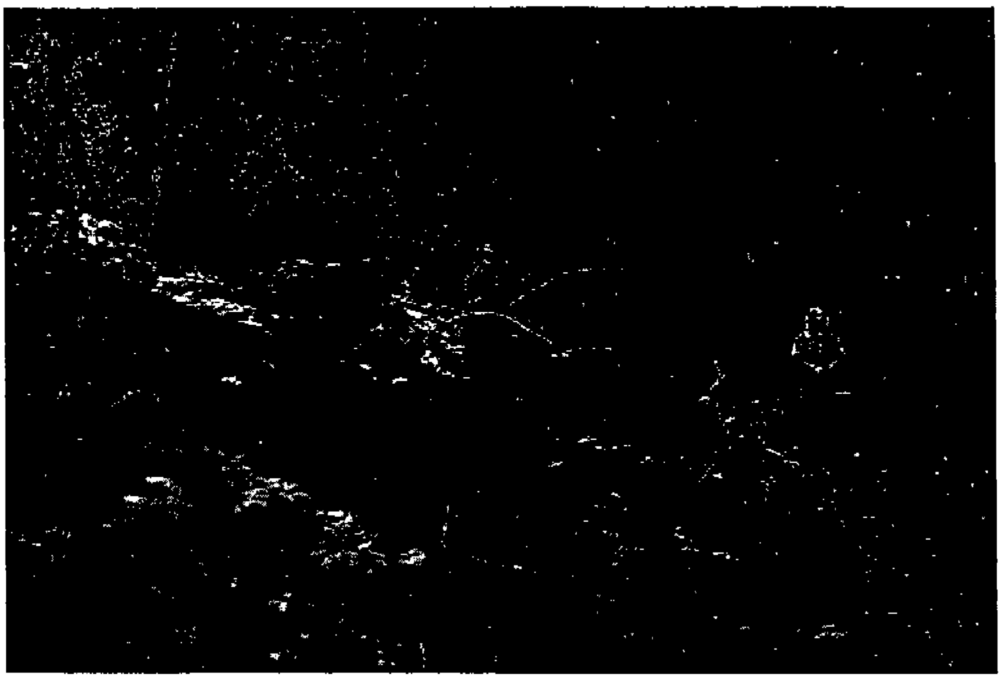


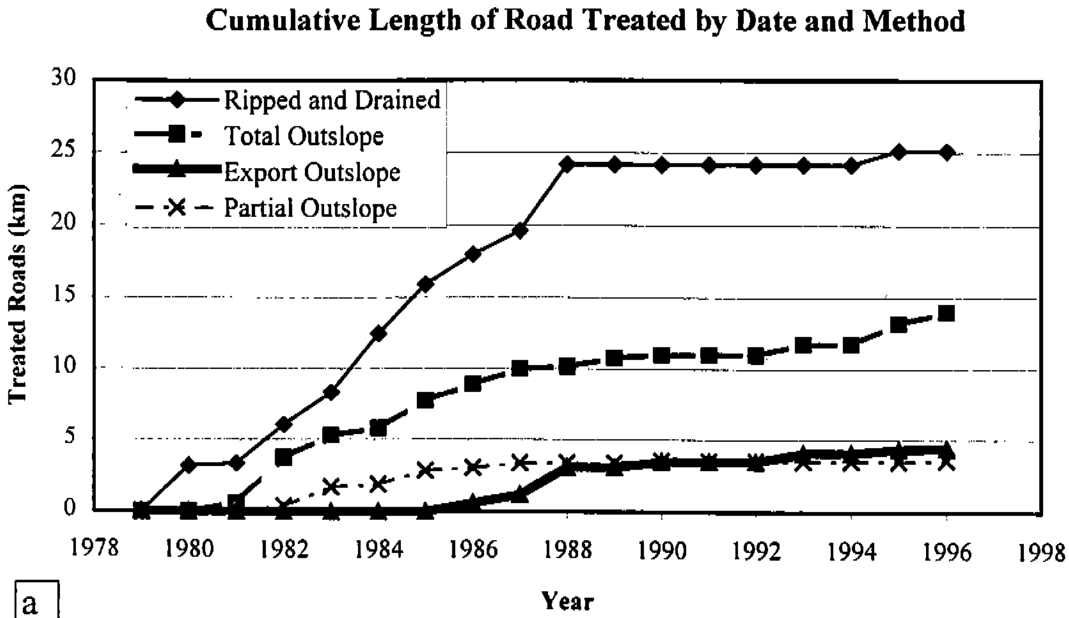
Figure 8: In recent years, wood has been placed on treated road benches as a final step.

20,000 m^3/km of treated road, or 30,000 to 40,000 yd^3/mile). Because surface erosion is not considered to be a major sediment source (Kveton and others, 1983), and natural revegetation is rapid in this region, little mulching or replanting has been done in recent years.

The cumulative length of road treated by the different methods is shown in Figure 9a. Most roads that were ripped and drained were treated prior to 1988, and most export outsloping occurred after 1988. This means that most minimally treated roads were subject to more storms than roads which had more intense levels of treatment. A greater length of road was treated in early years, when treatments were still being refined. Due to budget constraints and more intensive treatments in later years, fewer road segments were treated in more recent years. Figure 9b shows the cumulative length of road treated by hillslope position. More lower hillslope roads were treated in the first few years of the restoration program than roads in upper and middle hillslope positions, and overall more lower hillslope roads were treated. The implications of these interactions among date of treatment, treatment method and hillslope position are discussed more fully later.

Methods

By 1997, the National Park Service had treated 300 km (about 190 miles) of haul roads in Redwood National Park A pilot study on a small sample of roads (Bloom, 1998) showed that hillslope position was a significant variable in assessing erosion from both untreated and treated roads. In this study, all treated roads were subdivided into 1.6 km (1 mile) road segments, and stratified into three hillslope positions (upper, mid-slope and



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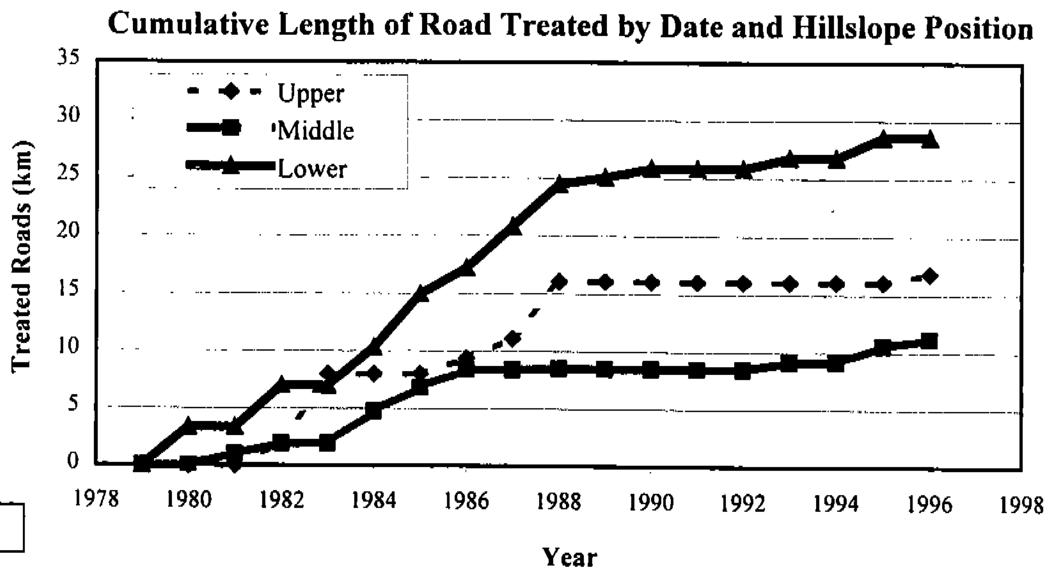


b

Figure 9a) Cumulative length of sampled roads by date and method of treatment

b) Cumulative length of sampled roads by date and hillslope position lower) based on the distance from the basin divide to the stream channel. The classification was based on the distance of the road from the adjacent ridgetop to the nearest high-order stream channel. In this catchment, hillslope position is related to slope gradient, with upper, middle and lower hillslopes averaging 25, 35, and 40 percent, respectively. It was difficult to accurately measure hillslope gradient at treatment sites, because thick vegetation and large road prisms obscured the original topography. For this reason, hillslope position is used as a surrogate for hillslope gradient. Because the streams in this study are highly constrained within steep, V-shaped valleys, 'lower hillslope roads' do not include any roads on floodplains or terraces.

Forty road segments were selected randomly for field mapping, but two segments, later deemed inaccessible, were not surveyed. During the field mapping phase each road segment was further subdivided into 'stream crossings' where a culvert had been removed, and intervening 'road reaches' which were treated by a variety of methods. Geomorphic maps that were constructed when the roads were first treated were used to supplement field observations to reconstruct site conditions at the time of treatment. Each sampled road segment comprised several treatment sites, representing both stream crossings and road reaches. Consequently, the inventory of 38 segments of treated roads (61 km, or 38 mi) resulted in a data set consisting of 207 crossings and 301 road reaches. Mean crossing length was 26 m ($\pm$ 17 m) and mean road reach length was 116 m ($\pm$ 84 m). Each excavated stream crossing and treated road reach had a separate inventory form with pertinent site information, map and erosion measurements.

Several types of post-road removal erosion were measured: mass movement, bank erosion and channel incision, and gullying. The inventory form used at each site is shown in Appendix A. Because previous studies had shown surface erosion from treated roads delivered a small proportion of the total sediment in this catchment (Kveton and others, 1983), surface erosion on the treated road bench or crossing was not measured. Sediment delivery was estimated by measuring the void left by bank erosion or mass movement features and measuring the dimensions of the downslope deposit, if present. Commonly, the toe of the landslide entered a stream channel, and the eroded material had been transported from the site by the time of the field mapping. The minimum size of gully measured was 0.1 m^2 in cross-sectional area. Type and density of vegetation on the site were also recorded. Many road reaches were thickly vegetated, which obscured small post-treatment erosion scars.

Factors used in the analysis of erosion and sediment delivery from treated road reaches were: hillslope position (upper, mid-slope, or lower); bedrock (schist, sandstone, or other); treatment type (ripped and drained, partial outslope, total outslope, export outslope or fill site); time period of restoration activity (1980-1983, 1984-1987, 1988-1991, and 1992-1996); and hillslope curvature (convex, planar, or concave). For stream crossings, the factors used were: bedrock type, date of treatment, drainage area, channel gradient, volume excavated from channels, step frequency and elevation drop due to steps. A more complete description of the statistical analysis used in this study is included in Appendix B.

Because road reach boundaries were based on the spacing between stream crossings, road reaches were of unequal length. Consequently, erosion from road reaches was normalized by the length of road reach (m^3/m of road). In contrast, crossing erosion was expressed as 'm^3 eroded per excavation.' It might also be preferable to express channel erosion volumes as a normalized value (m^3/m of channel), but in the field it was difficult to accurately determine the length of the excavated channel. Post-treatment channel adjustment upstream and downstream of the excavated channels blurred the boundaries of the excavated channel, and in many sites post-treatment erosion extended beyond the limits of the crossing excavation itself.

The treatment method for stream crossings (removal of culverts and reshaping streambanks) differed from that of road reaches (decompacting, draining or recontouring the road bench). Also, fluvial erosion (channel incision and bank erosion) caused most post-treatment erosion in excavated stream crossings, whereas mass movements accounted for three-fourths of the erosion from road reaches. For these reasons, the analysis considered data for stream crossings separately from road reaches.

The results of the erosion measurements are reported as two values: 1) "total erosion since treatment" in cubic meters (a measure of the volume of voids from mass movement, channel erosion or gullying on the treatment site) and 2) "sediment delivery to streams," in cubic meters, (the volume of the voids minus the volume of downslope deposits). Although the measure of voids on the treatment site is straightforward, the determination of how much of the eroded material actually reached a stream was somewhat subjective. Consequently, the estimates of sediment delivery from some sites are not as accurate as those of total erosion.

The date of treatment of the inventoried sites ranged from 1980 to 1996, and by 1997 when the sites were mapped, most road reaches and crossings were heavily revegetated with shrubs, hardwoods and some conifers. Thick revegetation (for example, Figure 2d) on most of the treated road reaches hindered a close inspection of the ground surface. Minor slope failures and gullying may have been overlooked. For this reason, there was an estimated detection limit of a few cubic meters in the assessment of erosion from road reaches, and only 20% of the road-reach sites had detectable erosion. In contrast to road reaches, 96% of treated stream crossings exhibited detectable levels of erosion (although most channel adjustment was minor). The entire length and width of the excavated channel were surveyed, so detection of erosion was not a problem.

Results and Discussion

Distribution of treated roads across sampling strata

The complete data sets for inventoried road reaches (RR) and excavated stream crossings (RX) are listed in Appendix C. Due to the history of the watershed restoration program at Redwood National Park, not all road types and road treatment techniques are equally distributed across time and space. Several variables were not independent of one another: year of treatment, method of treatment, and hillslope position. This fact is illustrated in Tables 1 and 2, which show the percentages of road length sampled in different categories. For example, 50% of the sampled roads were on lower

Table 1: Percentage of sampled road length according to hillslope and treatment types

	Road Rehabilitation Technique					
Hillslope Position	Ripped and Drained	Partial Outslope	Total Outslope	Export Outslope	Fill Site	**Total**
Upper	13%	5%	9%	<1%	3%	**30%**
Mid-slope	8%	2%	9%	<1%	1%	**20%**
Lower	21%	6%	7%	12%	4%	**50%**
Total	**42%**	**13%**	**25%**	**12%**	**8%**	**100%**

Table 2: Percentage of sampled road length according to bedrock, hillslope curvature, and date of treatment

Bedrock Type		**Hillslope Curvature**		**Date of Treatment**	
Schist	72%	Concave	25%	1980-1983	30%
Sandstone	22%	Planar	19%	1984-1986	32%
Other	6%	Convex	56%	1987-1991	27%
				1992-1996	11%

hillslope positions. This does not mean there were originally more roads on lower hillslopes, but that the restoration program targeted such roads for early treatment, leaving more upper hillslope roads untreated. Export outsloping was more commonly prescribed on lower hillslope roads, so few of the randomly selected road reaches in upper and mid-slope positions had this treatment technique applied. Early in the program, more roads were minimally treated, and total outsloping was more common in later years. Because of budget constraints and the use of more expensive techniques, fewer roads were treated in the period 1992-1996, so the length of treated road in this category is less than for other time periods. Consequently, any extrapolation of the results of this study must consider the constraints placed by the distribution of sampled road reaches across the various strata.

Stream Crossings

The total amount of material eroded from 207 crossings following treatment was 10,500 m^3, or about 50 m^3 /crossing. Although this represents a direct contribution of sediment to perennial streams, it is likely that, if these crossings had not been treated, much more sediment would have eventually been eroded and delivered into streams. For example, 220,000 m^3 of road fill was excavated from the crossings during treatment (1060 m^3/crossing) which represents the maximum volume of erodible material if those crossings had remained intact. In reality, not all the road fill actually erodes when a crossing fails. In the Garrett Creek catchment (a tributary upstream of the study area), Best and others (1995) determined the average erosion from 75 failed crossings that had not been treated was 235 m^3. On the other hand, by excavating crossings and restoring natural drainage patterns, diversion of flow from the natural channel is prevented. Best and others (1995) showed that at locations where roads did cause streams to divert (at one-fourth of the crossings) the average erosion was 2650 m^3. These lines of evidence suggest that the likely volume of erosion from the excavated crossings would have been at least four times greater, and probably more, if they had not been treated.

Most excavated stream crossings produced very little sediment. (Crossings which had debris torrents originating upslope and off-site of the crossing excavation were not included in this analysis because the purpose was to look at the effectiveness of the road treatment itself). Twenty percent of the excavated stream crossings produced 73 percent of the total volume eroded from stream crossings (Figure 10a). Klein (1987) and Bloom (1998) suggest that most channel erosion occurs in the first few floods following treatment, and later adjustments of the channel form are smaller in magnitude. Virtually all the road fill eroded from the treated channels was transported off site by the time the crossings were inventoried.

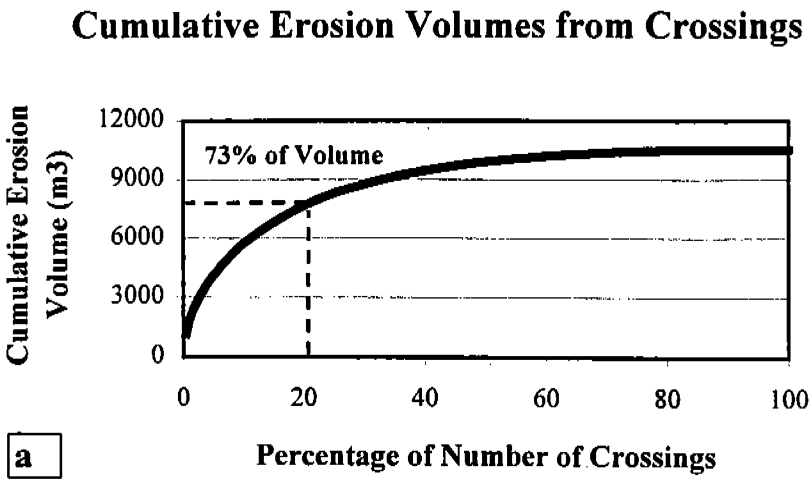
Channel incision and bank erosion were the most common forms of post-treatment erosion in crossings. Only two explanatory variables were significant in the best-fit regression model:

$$\text{Volume eroded } (m^3) = 20.8 + 0.041 \text{ (stream power)} + 0.009 \text{ (volume excavated, } m^3).$$

The greater the stream power and the larger the excavation, the more the channel eroded following treatment. Deeply incised channels that required more fill to be excavated were more vulnerable to post-treatment erosion than shallow crossings with less road fill because the reshaped streambanks were steeper and more likely to fail. The regression model was statistically significant at the 99% confidence level; however, the fitted model only explains 18% of the variability in post-treatment erosion. Erosion following treatment is highly variable, and many site-specific conditions (such as the presence of bedrock, springs, or poorly drained soils, or incomplete excavations) can influence post-treatment erosion as well.

Road Reaches

The total amount of material eroded from treated road reaches was 25,900 m^3. Most (77%) of this erosion was attributed to mass movement processes, primarily road fill failures. Of the total erosion from road reaches, 74% of the eroded material was delivered to a stream channel. Most treated road reaches performed well and produced very little sediment. The cumulative distribution of erosion from road reaches in even more highly skewed than that for road crossings (Figure 10b). Twenty percent of the



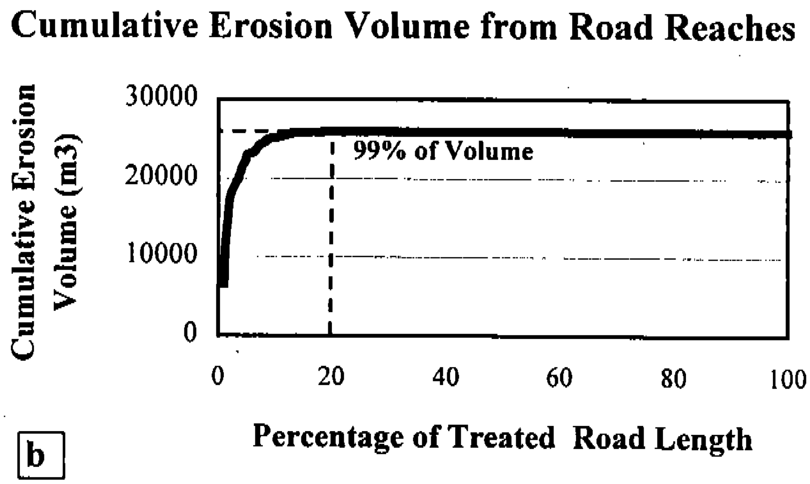


Figure 10a) Cumulative plot of total erosion from excavated crossings

b) Cumulative plot of total erosion from treated road reaches treated road reach length produced 99% of the total erosion from treated road reaches. Total post-treatment erosion from 61 km of road, including both fill failures and stream crossing erosion, was 37,000 m^3 (600 m^3/km of road); total sediment delivery was 29,500 m^3 (480 m^3/km of road).

Four variables were found to be statistically significant in explaining post-treatment erosion: hillslope position, date of treatment, treatment type, and an interaction term (hillslope position * treatment type). The results of the statistical analysis can be expressed by the odds of failure (that is, erosion occurred on the road reach). The odds of failure of roads treated in the early part of the program (1980-1983) were 6.8 times greater than the odds of failure for roads treated later (1992-1996). Similarly, the odds of failure for roads in lower hillslope positions were 51.3 times those of upper hillslope roads, and the odds of failure for mid-slope roads were 5.3 times those of upper slope roads (see Appendix B for details).

Although the model was significant at the 99% confidence level, the percentage of deviance explained by the model is only 13.4%. Erosion on treated road reaches was highly variable, as it was for treated stream crossings. Besides the geomorphic variables considered in this analysis, road reach erosion is also influenced by site specific conditions, such as the presence of seeps, depth to bedrock or a history of past mass movement activity. Even though bedrock type was not a significant variable in this regression model, a finer distinction of bedrock based on the degree of fracturing, shearing and erodibility in individual units may be worth exploring in the future.

Table 3 contrasts sediment delivery under different treatment and hillslope conditions. On upper hillslopes, sediment delivery from all treatment types is low. Even minimal treatment seemed to be sufficient in preventing erosion on these sites. This suggests that, except for sensitive geomorphic locations such as headwater swales, a low intensity (and concomitantly, less expensive) treatment is adequate for upper hillslope roads. Sediment delivery from mid-slope roads was also low, except for those that had minimal treatment. For effective sediment reduction, more intensive treatment, such as partial or total outsloping, is warranted on mid-slope roads.

Table 3: Volume of sediment delivered to channels from treated road reaches, reported as m^3/km of road length (yd^3/mile)

	Road Rehabilitation Technique				
Hillslope Position	Ripped and Drained	Partial Outslope	Total Outslope	Export Outslope	Fill Site
Upper	10 (21)	10 (21)	10 (21)	N/A*	0 (0)
Mid-slope	310 (650)	0 (0)	20 (42)	N/A*	80 (170)
Lower	640 (1350)	550 (1160)	630 (1330)	920 (1940)	40 (85)

*Less than 5 samples in this category.

Lower hillslope roads performed the worst, no matter which treatment was used. It is interesting to note that the most extensive treatment method (export outsloping) was associated with the highest sediment delivery to streams from road reaches in lower hillslope positions. The expectation of the road rehabilitation program had been that the more intensive the treatment, the less post-treatment erosion would occur. Nevertheless, this result regarding export outsloping should not be automatically interpreted as a general failure of the technique. Professional judgement is used when restoration treatments are formulated for a given road reach. Park staff who prescribed the high intensity treatment of export outsloping recognized some inherent instability of the road reach, based on evidence of past mass movement, the presence of seeps in the cutbanks, incipient failure of the road bench, etc. Consequently, these road reaches were among the most unstable even before road treatments were applied, and so might be expected to erode more following any type of treatment. On the other hand, because more land area is disturbed using this treatment method, and the capacity of the road bench to store material from cutbank failures is eliminated, it may be that the treatment allows for greater sediment delivery than other treatments. A closer examination of the conditions under which export outsloped road reaches fail and deliver sediment is necessary to distinguish the causal mechanism.

Table 3 illustrates that road rehabilitation efforts following road construction in steep, lower slope positions have a high failure rate and contribute much sediment to streams, no matter what type of treatment is used. If sediment reduction from roads is the objective in a catchment, Table 3 suggests the need to avoid road construction (or improve road construction techniques) in these steep, streamside areas. Not only are these likely spots for erosion while the road is in place, but also subsequent treatment of the road may not be effective in eliminating road-related sediment production.

Basin-wide Perspective of Sediment Production

No direct measurements of sediment yield from treated roads during the 1997 storm are available. The numbers from the present inventory can be roughly compared with measurements made at the gauging station at the mouth of Redwood Creek (drainage area = 720 km2). The suspended sediment load for Water Year 1997 was 1,700,000 Mg (metric tonnes). The inventory of 61 km of treated roads showed a contribution of 29,500 m^3 of sediment to streams (480 m^3 per km of treated road). If the randomly sampled roads are representative of all treated roads and this rate is applied to the entire 300 km of treated roads in Redwood National Park, 144,000 m^3 of sediment probably entered streams from treated roads. The exact timing of erosion for most cases in not known, except that it occurred sometime following road treatment, and not all of this sediment was produced in the 1997 storm. Consequently, sediment yield from treated roads represented a contribution of about 233,000 Mg to the basin's sediment load (assuming a bulk density of 1.62 gm/cm^3) sometime during the last 20 years. Some of the coarse particles in eroded road fill were transported as bedload, some broke to suspendable size particles during transport, and some sediment was temporarily stored in small stream channels, but little is known about the specifics of sediment routing through these steep, low-order channels.

If the roads had remained untreated, they would eventually fail and contribute sediment to streams. Ninety three miles of untreated roads in the lower Redwood Creek basin were inventoried following the 1997 flood. Bloom (1998) provides an in-depth analysis of this inventory, but the results are summarized in Table 4. In this case, upper hillslope roads delivered more sediment to streams than lower hillslope roads. Many road fills located in headwater swales failed during this storm, and resulted in large debris torrents. This points out the importance of identifying sensitive terrain, such as

Table 4 : Summary of 1997 road reach failures on untreated roads:

	Upper and Mid-slope Roads	Lower Hillslope Roads
Miles of Road Inventoried	64	29
Number of Failure Sites (n)	16	17
Mean Failure Size (yd^3)	3714	1010
Median Failure Size (yd^3)	2000	400
Standard Deviation (yd^3)	903	1725
Minimum Failure Size (yd^3)	10	50
Maximum Failure Size (yd^3)	10000	7000
Total Erosion for Category (yd^3)	59426	17175
Normalized Erosion Volume (yd^3/mi)	929	601
Total Sediment Delivered to Channel (yd^3)	52384	15105
Normalized Sediment Delivery (yd^3/mi)	819	528
Number of Failure Sites/Mile of road	0.3	0.5

headwater swales, because not all "upper hillslope" roads are low risk. Also, because the roads in the worst terrain (steep, inner gorge slopes) have already been treated through the Parks' restoration program, the remaining lower slope roads that were available for this inventory were not the worst offenders, and they delivered less sediment on a per mile basis than upper hillslope roads.

Other inventories road inventories show higher erosion rates for untreated roads. Based on an inventory of 330 km of untreated roads in nearby basins, Weaver and Hagans (1999) estimated past road-related sediment delivery to be 720 m^3/km of road

(1523 yd^3/mile), and future potential sediment delivery without road treatment to be an additional 820 m^3/km (1723 yd^3/mile), for a total of 1540 m^3/km (3246 yd^3/mile). In a similar study based on 140 km of untreated roads in the Redwood Creek catchment, Bundros and Hill (unpublished data) reported past and potential sediment delivery from about 145 km (90 miles) of roads to be 1450 m^3/km (3060 yd^3/mile). Untreated roads in the Garrett Creek catchment produced much more sediment (4670 m^3/km or 9850 yd^3/mile)), most of which originated from debris torrents caused by stream diversions (Best and others, 1995). By removing culverts and restoring natural drainage patterns, park staff have removed the risk of stream diversions that would cause such debris torrents. None of the 207 excavated crossings examined in this study had diversions or debris torrents related to road treatment. These different lines of evidence suggest that, although road restoration in Redwood National Park did not completely prevent sediment production from removed roads, it does substantially reduce the long-term sediment risk from abandoned roads.

In contrast to the road inventories described above, a recent study by Rice (1999), also conducted in the Redwood Creek basin, reports an erosion rate of only 177 m^3/km (370 yd^3/mile) of untreated logging road during the period 1995 to 1997. The hillslope position of these sampled road plots was not reported. These roads were located farther inland than the roads in Redwood National and State Parks, and they did not receive as much rainfall in the 1997 storm. From December 29, 1996 to January 1, 1997, 14.28 inches of rain was recorded at the Elk Camp raingage (in the lower Redwood Creek basin adjacent to the roads inventoried in the park study), as opposed to 6.4 inches of rain at Redwood Creek near Blue Lake, and 10.9 inches at Lacks Creek, which are raingage stations closer to the roads in Rice's study. This means that the roads in Rice's study area were only subjected to a rainfall event of less than five-year return interval. Under these relatively low rainfall intensity storms, few culverts failed, as might be expected. Most road-related erosion in the past has been linked to culvert failures and diversions that occur during high intensity rainfall events. It is likely that the erosion rate reported by Rice (1999) does not represent the full erosion potential from untreated roads if these roads underwent a high intensity rainfall event.

Vegetation

Revegetation of disturbed sites will help reduce surface erosion and will add root strength to the remaining road fill. There is also a concern regarding conifer regrowth in disturbed riparian areas (those in excavated stream crossings) and the recruitment potential for large woody debris in streams. Revegetation may also have an impact on stream temperatures as the levels of shading and canopy cover change through time. During the field inventories, several observations of species, density and cover were made on the rehabilitation sites (See Appendix A for the type of information collected). Heights of vegetation were measured with a survey rod. Rigorous sampling with vegetation transects was not conducted; instead visual estimates were used to provide a general picture of the degree of revegetation occurring on the sites.

In general, the west side of Redwood Creek is underlain by schist bedrock and the east side is underlain by sandstones and mudstones, and vegetation differed on the two types of terrain. Red alder (*Alnus rubra*) was the dominant species revegetating the treated road reaches on the schist terrain; whereas shrubs (*Ceanothus* and *Baccharis*) and grasses were dominant on the drier, east-side sandstone slopes (Figure11). Excavated stream crossings were generally wetter, and had more alder and some willow growing on the reshaped streambanks (Figure 12). After 3 to 5 years, the alders generally formed a thick cover over the small streams in the excavated crossings, and by 10 to 15 years there was much shade over the streams. Little of the shade was attributed to conifers, however. The heights of the alders corresponded to the age of treatment, with the oldest sites having the highest trees (Figure 13). Density of vegetation on most sites was thick (average spacing of stems was 2 ft). In this coastal environment, natural revegetation of the treated roads is generally rapid, except for hot, dry, rocky sites.

Although alder dominated the regrowth of treated sites, many other species were also present. Figures 14 and 15 show the sub-dominant species (i.e. species with a rank of '2') on road reaches and in crossings. Conifers, both redwood and Douglas fir, are becoming well established under the alder canopy at about one-fourth of the sites. On many sites, although conifers are present, the subdominant species is herbaceaous or shrubby at this point.

Non-native plants commonly invade disturbed lands, and the field inventories included a search for such exotics. Common exotics found were foxglove (*Digitalis)*, pampas grass (*Cortaderia selloana)*, Scotch Broom (*Cytisus scoparius)*, and Himalaya berry (*Rubus discolor)*. Few stream crossings had exotics present, but many treated road reaches on sandstone terrain had some exotics present (Figure 16). These will probably die out as redwood and Douglas fir become reestablished on the sites.

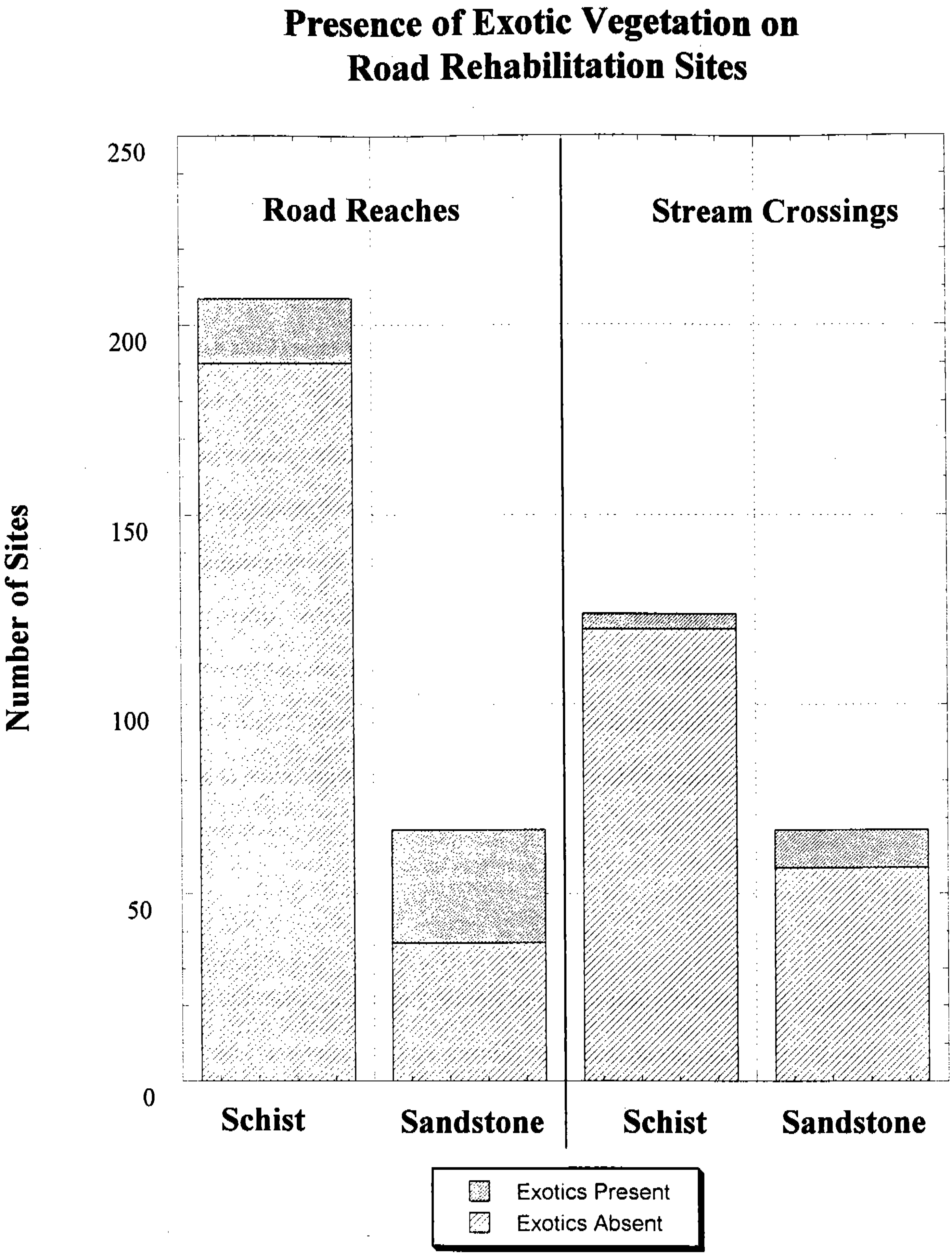


Figure 16: The number of treated road reaches that had exotic vegetation growing on them

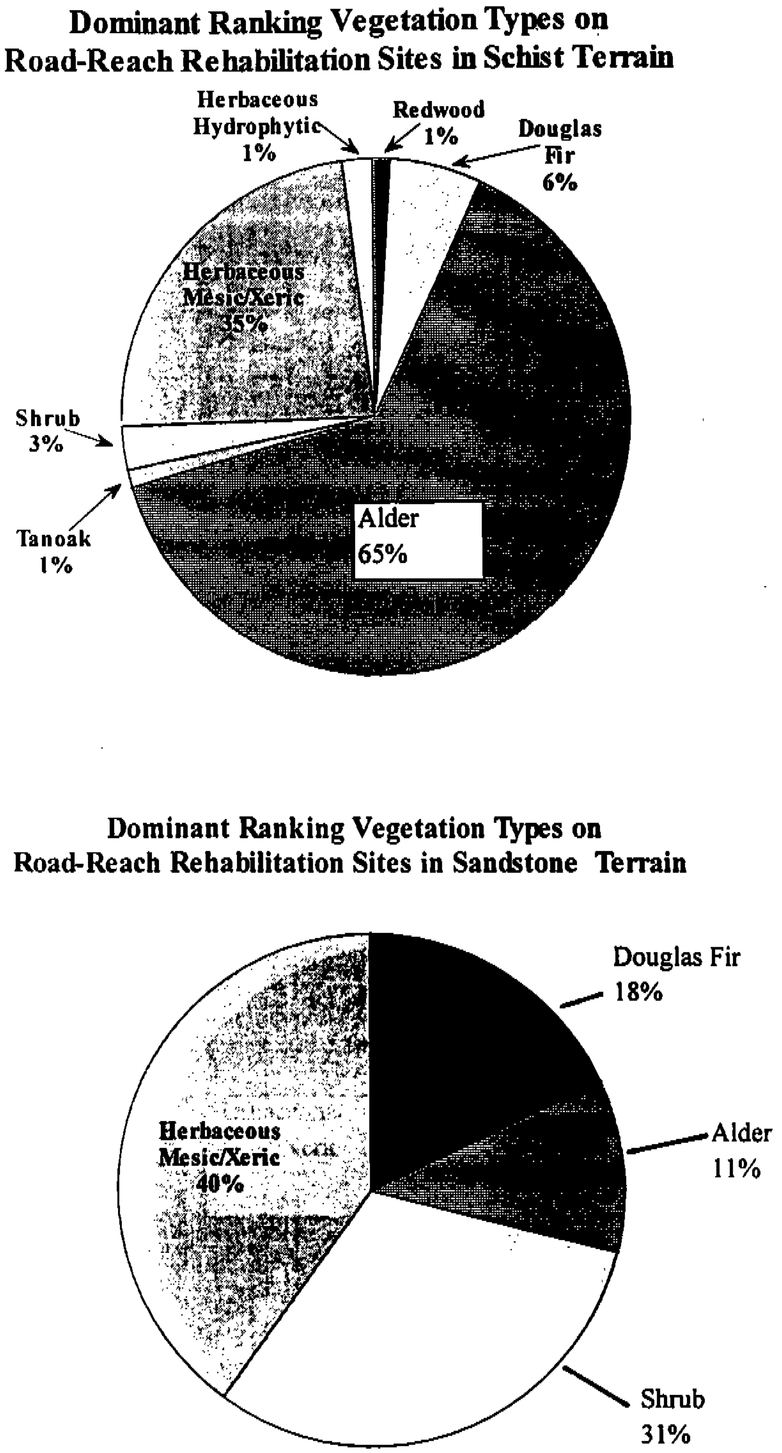


Figure 11: The dominant species growing on treated road reaches in a) schist terrain, and b) sandstone terrain

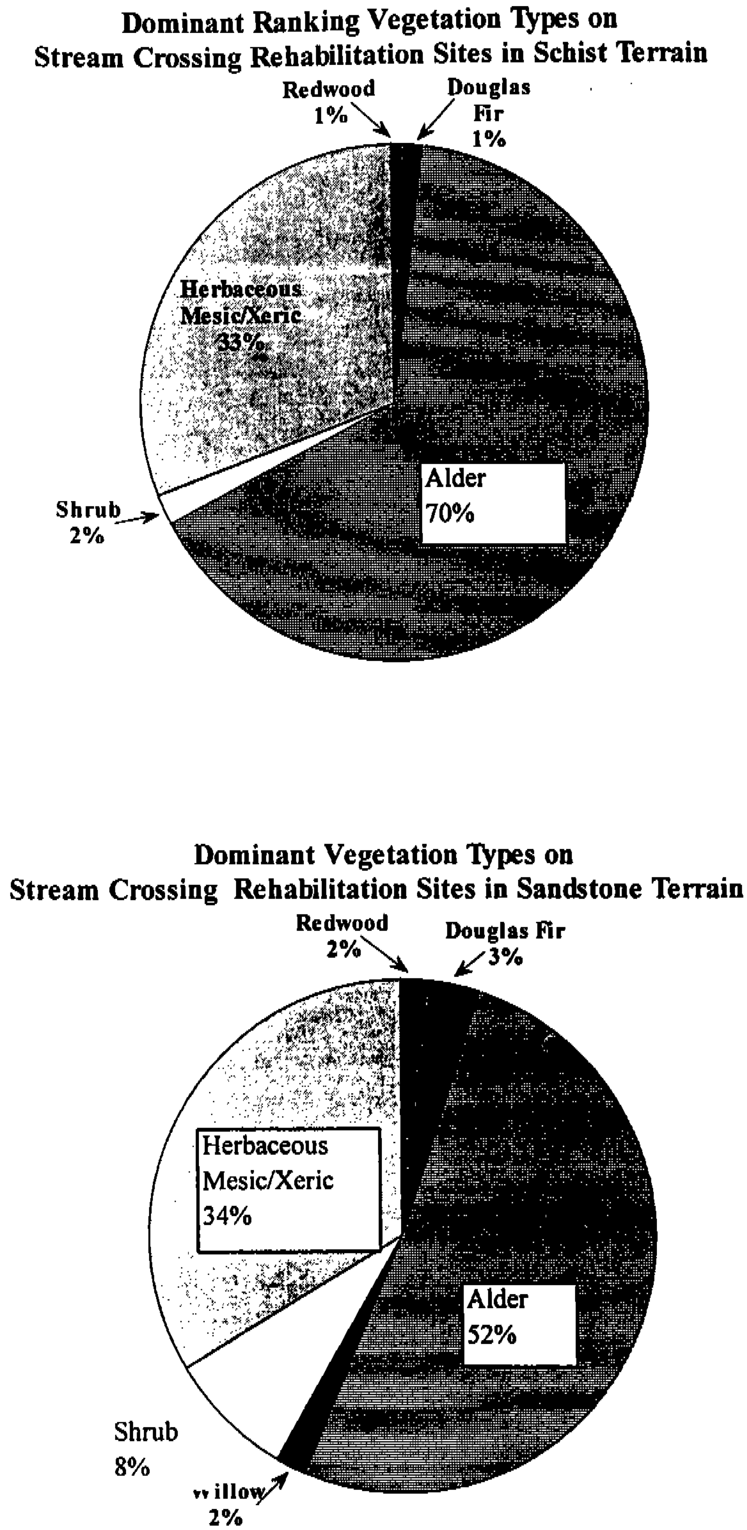


Figure 12: The dominant species growing on excavated stream crossings in: a) schist terrain, and b) sandstone terrain

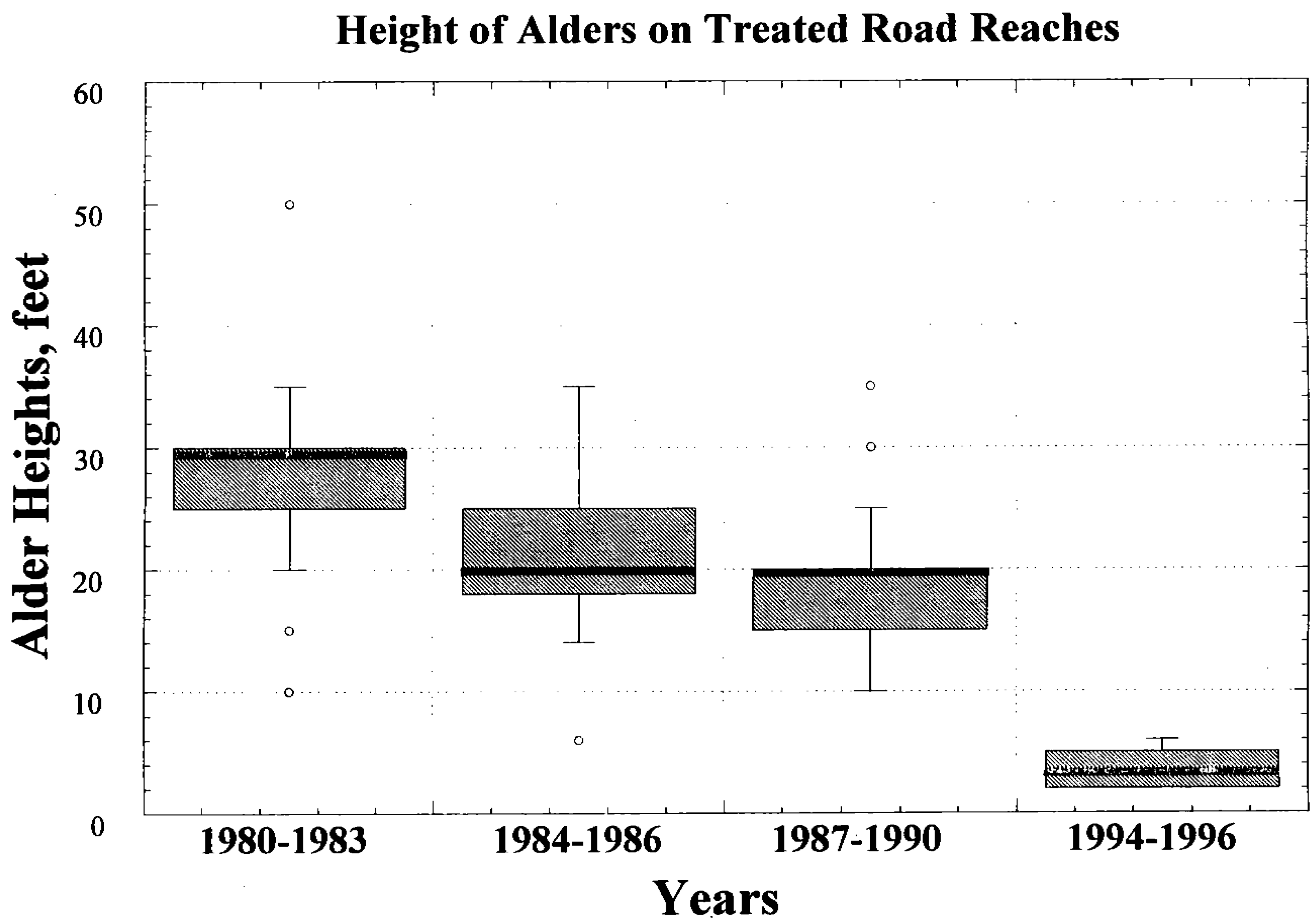


Figure 13: The average height of red alders growing on treated road reaches, by date of treatment.

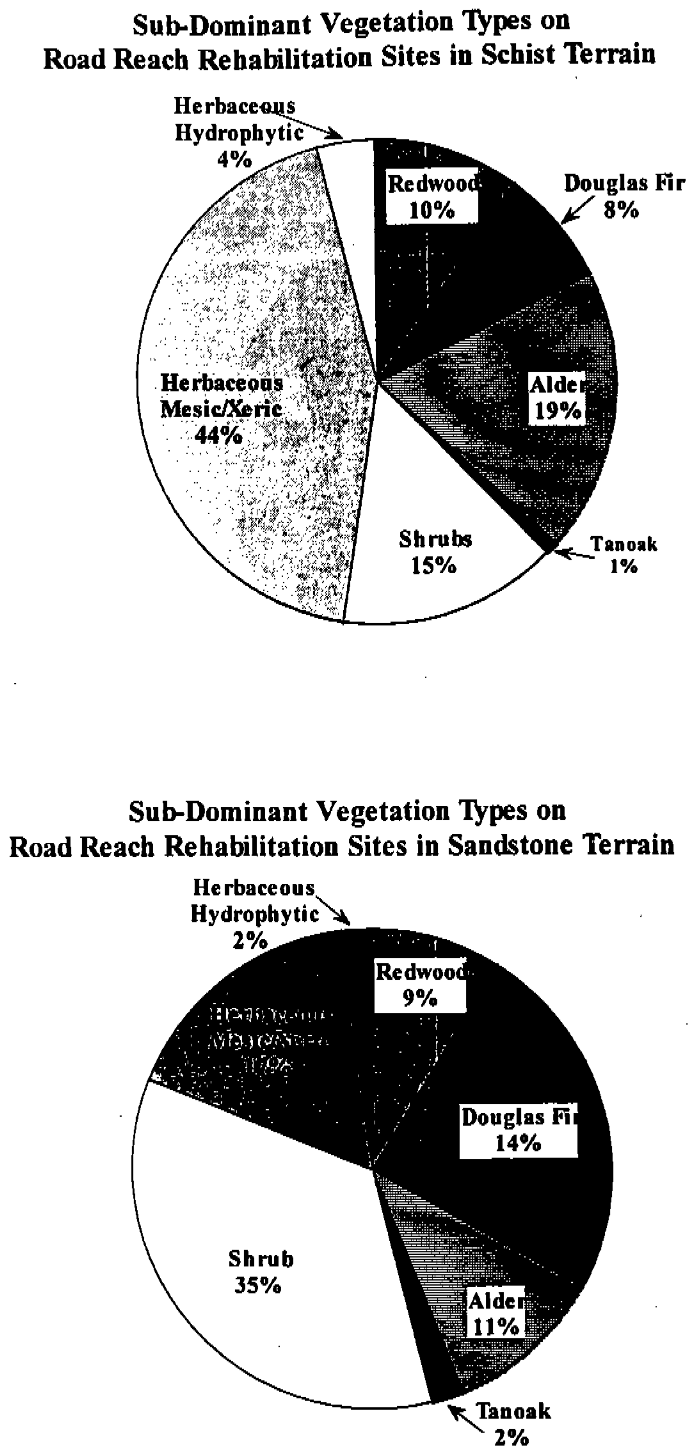
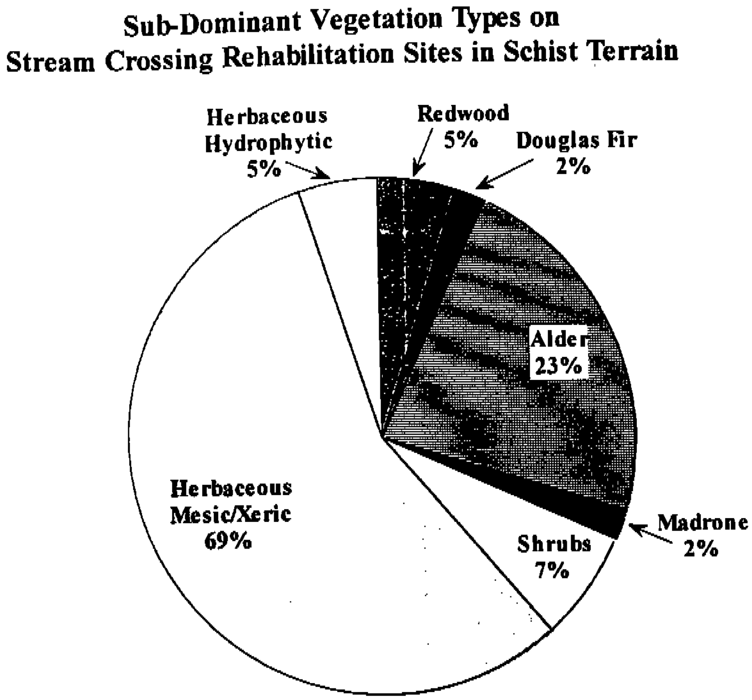


Figure 14: The subdominant species growing on treated road reaches in:
a) schist terain, and b) sandstone terrain



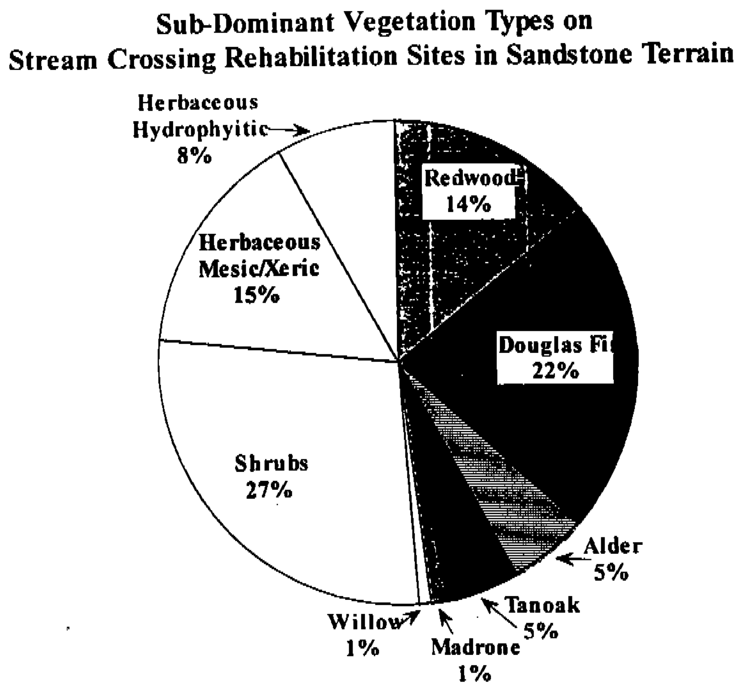


Figure 15: The subdominant species growing on excavated stream crossings i a) Schist terrain, and b) Sandstone terrain.

Common Problems

Most treated road reaches performed very well after a large storm. When there were problems, the most common causes were 1) the treated site was also a site of past mass movement activity, 2) unstable road fill was left on the steep, outboard edge of a road bench and 3) seeps were not well identified or sufficiently drained, and road fill became saturated. Where inboard ditches were not adequately obliterated and drained, the ditches ponded water, leading to local saturation of the road fill. In some cases, landslides originating from upslope of the road bench eroded the treated road site. Stream crossings incised when they were not excavated to the original channel bottom Therefore, partial excavation of crossings (for example, removing a perched culvert, but not excavating the road fill to the original channel bed) is not recommended. Careful mapping of road, hillslope and channel conditions can help identify problem areas during the planning phase, and more intensive treatments could be prescribed in geomorphically sensitive areas.

Costs

In this section, a summary of costs for various road treatments will be presented, but the reader must be aware there are many constraints on the data. Costs for road restoration work were based on project reports prepared by the geologists in charge of a restoration site, combined with maps of the road showing the various rehabilitation prescriptions. Many different people worked on many types of sites during the last 20 years, and the type of information and level of detail included on the maps and in the reports varied. Table 5 is a summary of project costs, based on the best available data. Some categories have a wide range of costs. Costs have not been adjusted for inflation. Part of the total project costs include miscellaneous charges, such as transportation into and out of a site, and time for moving to different work sites along a given road, that are not reflected in the 'cost per foot.' For all these reasons, these cost estimates should be only be used in a relative sense as a general guide for what the various treatments cost on these particular past rehabilitation sites, and should **not** be used as an estimate for planning new rehabilitation projects.

Crossing excavations averaged $2.42 per cubic yard excavated. Crossing excavations involving culvert removal represent a direct reduction in sediment yield, because it is likely that if the culvert failed, road fill in the stream crossing would directly enter a stream. The costs of treating intervening road benches varied widely, from $0.34/ft of road for ripping and draining the road bench, to $2.62/ft of road for total outsloping, to $11.58/ft of road for export outsloping. Obviously, decisions on what rehabilitation technique to use has a large impact on the cost of the project. It is imperative to understand the geomorphic setting and the erosion risks associated with a given road, as one weighs the costs and the probable effectiveness of various techniques. Some sensitive sites require intensive rehabilitation techniques, whereas other, more stable areas can be treated with less intensive techniques. The conclusions of which sites are most sensitive for the Redwood Creek basin, which has several fault zones and inner gorge areas, may be quite different from a sensitivity analysis conducted for other watersheds with different controls on erosion rates.

Table 5: Costs for Various Road Rehabilitation Projects

Road Name	PROJECT	BASIN	Year Treated	Number of crossings excavated	Number of Crossings Surveyed	Total Project Cost	Total Cost for Crossings	yd^3 Excavated (Crossings)	Cost per yd^3 (Crossings)
M-6-1	80-3	BRIDGE CREEK	1980		7				
2010	81-2	LOWER SLIDE CR	1981	14	5	$129,529	$28,806	6809	$4.23
C-30	82-1	EMERALD CREEK	1982	16	10	$133,761	$53,337	13203	$4.04
Y-LINE	82-3	DEVILS CREEK	1982	17	6	$93,241	$31,815	11660	$2.73
L-1-5	82-4	BOND CREEK	1982	29	14	$46,435	$40,560	18036	$2.29
Y-LINE	83-1	DEVILS CREEK	1983	16	4	$70,610	$49,511	20117	$2.46
M-3-1	83-2	BRIDGE CREEK	1983	16	10	$151,714	$12,829	9210	$1.39
UPPER D	83-4	G CREEK	1983	16	5	$70,610	$12,829	9210	$1.39
W-LINE	83-7	EMERALD CREEK	1983	18	20	$30,603	$9,552	7116	$1.34
C-LINE	84-5	FORTY-FOUR CR	1984	57	22	$98,485	$46,915	23095	$2.03
Y-LINE	85-1	DEVILS CREEK	1985	41	1	$108,818	$33,551	18875	$1.78
G-LINE	85-3	TOM MCDONALD CR	1985	34	11	$171,778	$58,208	19244	$3.02
C-50	85-4	MILLER CREEK	1985	8	2	$92,800	$9,359	6571	$1.42
M-7-4	86-1	BRIDGE CREEK	1986	1	1	$201,647	$4,548	973	$4.67
M-4.5	86-3	BRIDGE CREEK	1986	32	13	$110,689	$56,698	21217	$2.67
M-6-1	86-4	BRIDGE CREEK	1986	11	6	$96,512	$24,844	11511	$2.16
M-3-1-2	86-5	BRIDGE CREEK	1986	24	0	$99,857	$47,635	15200	$3.13
G-6	87-2	TOM MCDONALD CR	1987	9	3	$113,893	$14,827	4195	$3.53
M-6-2	87-3	BRIDGE CREEK	1987	20	9	$113,893	$43,872	22320	$1.97
M-3	87-5	BRIDGE CREEK	1987	34	5	$136,727	$44,074	35969	$1.23
LOWER M	88-1	MAY CREEK	1988	2	2	$10,451	$2,033	1250	$1.63
LOWER K	88-2	REDWOOD CREEK	1988	11	4	$207,673	$24,310	7650	$3.18
M-4-1	88-3	BRIDGE CREEK	1988	12	8	$164,874	$61,057	20060	$3.04
B-5-1	88-5	BRIDGE CREEK	1988	18	3	$73,486	$17,738	12994	$1.37
B-5-5-1	88-8	BRIDGE CREEK	1988	8	3	$23,774	$2,005	2380	$0.84
M-7	88-9	BRIDGE CREEK	1988	2	0	$18,842	$210		N/A
LOWER K	89-2	COYOTE CREEK	1989	6	6	$230,674	$84,313	19427	$4.33
M-7	90-3	BRIDGE CREEK	1990	9	3	$228,247	$46,775	13495	$3.47
K&K	93-2	REDWOOD CREEK	1993	9	8	$290,107	$42,490	21245	$2.00
				Sum = 490					
								Totals:	490 xings
								Average:	$2.42 /yd^3

	L	M	N	O	P	Q	R	S	T	U	V	W
1												
2	Costs for Total Outslope	Length of road -Total Outslope (ft)	Cost per ft of Total Outslope	Costs for Partial Outslope	Length of road -Partial Outslope (ft)	Costs per ft of Partial Outslope	Costs for Export Outslope	Length of road-Export Outslope (ft)	Costs per ft of Export Outslope	Costs for Rip and Drain	Length of road- Rip and Drain (ft)	Costs per ft of Rip and Drain
5												
6	$20,291	19278	$1.05	$3,421	1000	$3.42	$0	0		$5,392	10220	$0.53
7	$26,349	10352	$2.55	$15,582	4607	$3.38	$0	0		$3,474	12144	$0.29
8	$44,849	12468	$3.60	$0	0		$0	0		$1,115	6058	$0.18
9	$4,573	1320	$3.46	$2,001	n/a	n/a	$0	0		$3,216	19008	$0.17
10	$21,740	6923	$1.77	$83	50	$1.66	$14,242	1586	$8.98	$2,559	6493	$0.39
11	$30,565	6685	$4.57	$1,338	750	$1.78	$0	0		$2,671	9700	$0.28
12	$10,491	3953	$2.65	$0	0		$0	0		$4,198	9022	$0.47
13	$8,410	9126	$0.92	$0	0		$0	0		$962	7920	$0.12
14	$5,825	3755	$1.55	$0	0		$3,350	2015	$1.66	$4,643	13600	$0.34
15	$14,844	10205	$1.45	$6,176	4730	$1.31	$11,964	5380	$2.22	$4,654	3700	$1.25
16	$12,256	11071	$1.11	$0	0		$35,539	11078	$3.21	$0	0	$0.00
17	$43,881	4545	$9.65	$0	0		$0	0		$4,529	0	$0.00
18	$0	0		$0	0		$136,124	2933	$46.41	$1,438	1848	$0.78
19	$0	0		$0	0		$4,955			$987	850	$1.16
20	$0	0		$0	0		$33,004	900	$36.67	$200	40	$5.00
21	$0	0		$0	0		$0	0		$4,247	2771	$1.53
22	$3,853	556	$6.93	$0	0		$49,902	1430	$34.90	$1,999	5435	$0.37
23	$0	0		$0	0		$42,310	90	$470.11	$2,247	11162	$0.20
24	$14,966	2575	$5.81	$0	0		$13,220			$4,408	21759	$0.20
25	$0	0		$0	0		$0	0		$641	4148	$0.16
26	$8,579	2954	$2.90	$0	0		$89,098	2553	$34.90	$0	0	$0.00
27	$4,463	280	$15.94	$0	0		$66,452	2400	$27.69	$1,238	8712	$0.14
28	$0	0		$0	0		$6,700	698	$9.60	$14,749	24730	$0.72
29	$1,756	2372	$0.74	$0	0		$2,139	527	$4.06	$1,478	11770	$0.13
30	$60	90	$0.66	$0	0		$9,652	850	$11.36	$171	1050	$0.16
31	$11,760	2145	$5.48	$0	0		$76,062	2649	$28.71	$392	2798	$0.14
32	$35,455			$0	0		$77,446	17805	$4.35	$6,520		
33	$55,070			$0	0		$99,552			$2,920	11616	$0.25
34												
35												
36	$289,511	110653		$28,601	11137		$611,674	52804		$69,999	206554	
37		TOS =	$2.62/ft		POS =	$2.39/ft		EOS =	$11.58/ft*		R&D	$0.34
38								(without using values from the M-6-2 Road)				per ft

Rolling Dips

Another part of this study involved examining roads that were still open to traffic, but had rolling dips constructed at each road-stream intersection. Rolling dip design is explained thoroughly in Hafterson (1973). If a culvert fails (plugs with debris, runoff exceeds the culvert capacity, etc.), rolling dips are designed to funnel the water flowing over the road prism into the channel directly downstream of the road, and prevent the water from diverting down the road onto an unchanneled hillslope or into another drainage. Road fill at the rolling dips may erode when a culvert fails, but the magnitude of the erosion should be much less than if the runoff diverted down the road to another location, where it can cause gullies or road fill failures. Road dips should be designed so that vehicles can easily clear the dip crests and associated concavity in the road grade.

Ninety-six rolling dips on 15 miles of road in the Coyote Creek subbasin of the Redwood Creek basin were evaluated to assess their effectiveness. None of the culverts inventoried failed during the 12-year flood of 1997, so it was not possible to evaluate how effective the rolling dips would be under conditions of culvert failure. Instead, rolling dips basin were measured to calculate the approximate maximum amount of water that the dip could convey, and to then compare that capacity with the predicted flow during a 50-year recurrence interval flood event. The 50-year flood estimates were computed using the rational runoff method (Dunne and Leopold, 1978) for drainage areas less than 80 acres, and with the method of Waananen and Crippen (1978) for drainage areas greater than 80 acres. We recognize that as water flows through the rolling dip, the road fill in the dip may erode and the conveyance of the dip would increase during a storm. However, this comparison of the present rolling dip capacity versus the 50-year flood discharge is helpful in assessing whether dips will initially perform as planned.

Rolling dip parameters measured in the field (Figure 17) are:

1) *Minimum Depth* (d_{min}): Depth was measured along the cross section of the dip that was perpendicular to flow direction at the easiest exit point (minimum relief). This depth was measured from a level line (string with free-hanging carpenter's level from the dip crest to the road surface (measured to 0.1 ft.)

2) *Maximum Depth* (d_{max}): Measured by same technique as minimum depth, but the measurement is made at the point of maximum relief in the rolling dip (measured to 0.1 ft.)

3) *Top Width:* The width of the dip from the dip crest to the intersection with the road upslope, using a level line and carpenter level. The width was measured along the same level line as the minimum depth cross section. (again, perpendicular to flow) (measured to 1.0 ft.)

4) *Grade of Dip:* Percent slope from the inboard edge to the outboard edge of the dip, along the centerline of the rolling dip (measured to 1%)

5) *Road Bed Grade:* Percent slope of the road on either side of the dip (measured to 1%, along approximately 100 ft. length of road).

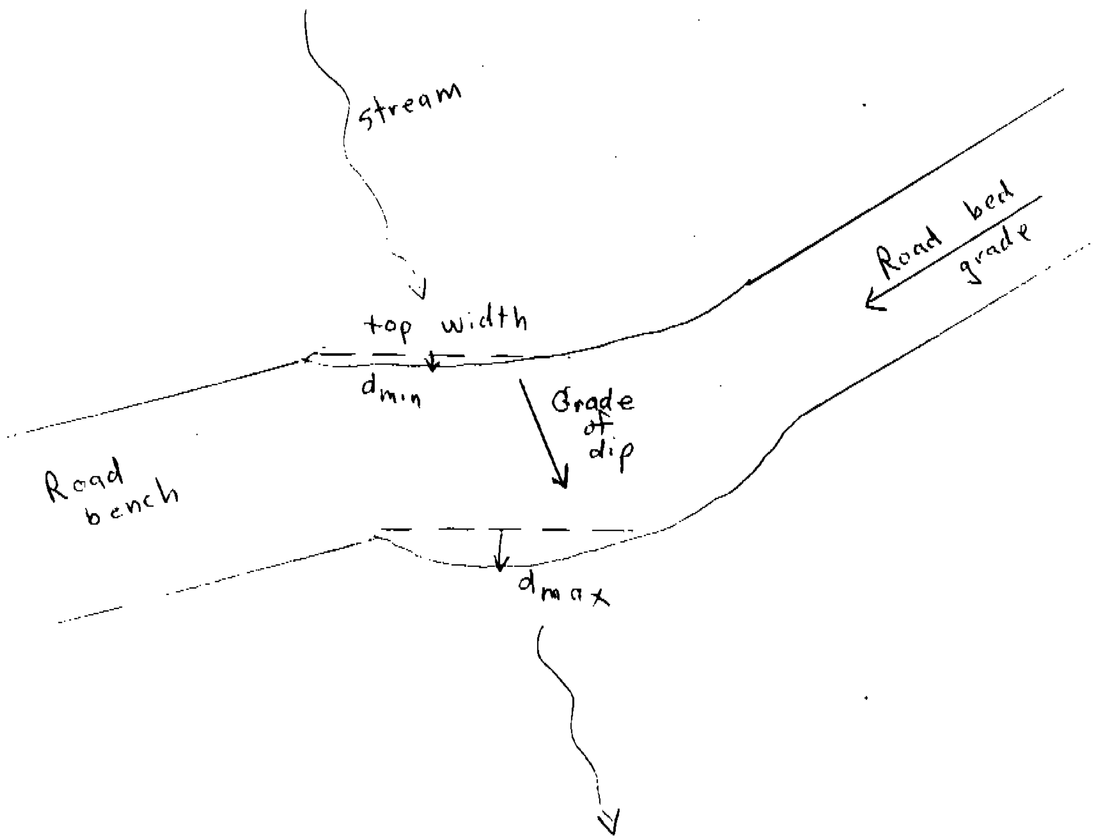


Figure 17: Measurements made on rolling dips.

The cross-sectional area of the dip was computed by two formulas (the area of a triangle ('a' on attached figure) and half the area of an ellipse ('b' on attached figure). These areas were then used in the calculation of carrying capacity of the dip. Manning's equation was used to calculate the velocity of water flowing through the dip:

$$v = 1.49 \frac{(d^{2/3})(S^{1/2})}{n}$$

where 'd' is the flow depth in feet, as an approximation of hydraulic radius, 'S' is the slope of the dip (ft/ft), 'v' is mean velocity (ft/sec), and 'n' is the roughness coefficient. An n-value of 0.03 was used, based on a review of the literature. The product of 'cross-sectional area of the dip' and 'water velocity' equals discharge. Two estimates of peak discharge, based on the two area calculations (triangle and ellipse), were averaged to obtain an estimate of the carrying capacity of the rolling dip.

Figure 18 shows the results of this analysis. Dips plotting above the line have a capacity greater than the 50-year flow. Almost all rolling dips in this study had sufficient capacities to carry runoff from a large storm, if the culvert failed. Field constraints, such as shallow culverts or the presence of bedrock in the road bench, sometimes make it difficult to construct a rolling dip as large as the design. This inventory on Redwood National and State Parks lands suggests that most rolling dips should perform well in the next large storm, if culverts fail.

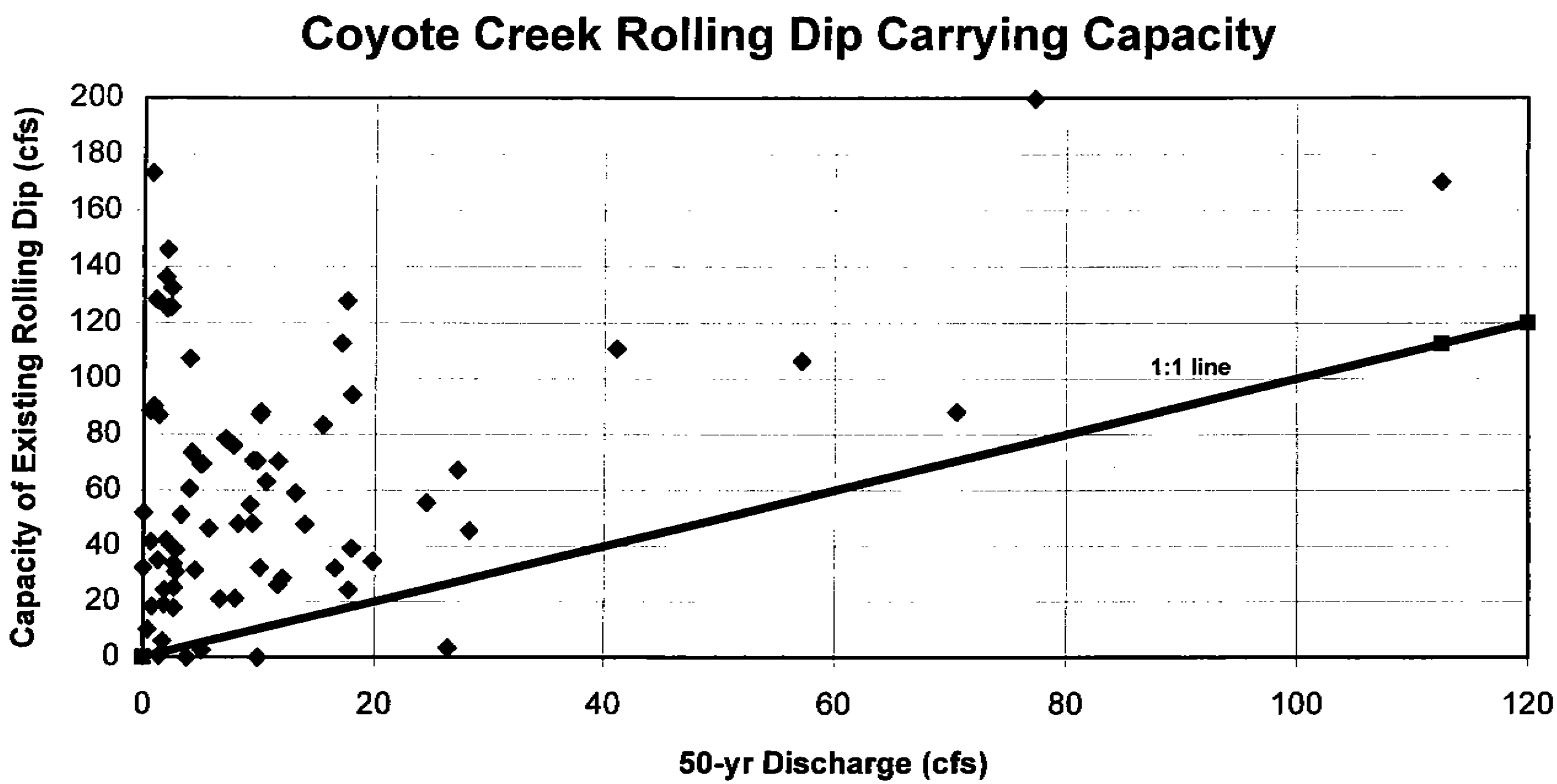


Figure 18: Comparison of the existing capacity of rolling dips to the estimated 50-year flood.

Conclusions

During the two decades following removal of unpaved forest roads, post-treatment erosion of both crossings and road reaches was highly variable. Treated roads contributed 480 m^3 of sediment to streams per kilometre of road, which was about one-fourth the sediment produced from untreated roads. Only 20% of the excavated stream crossings accounted for 73% of the post-treatment erosion from crossings. In stream crossings, post-treatment erosion was most strongly correlated to a surrogate for stream power (drainage area * channel gradient) and the amount of road fill excavated from the stream crossing during treatment.

Almost 80% of the treated road reaches had no detectible erosion following a 12-year recurrence interval storm. Even though most treatment sites were heavily vegetated within a few years of treatment, 5- to 15-year old vegetation did not prevent road fill failures on 20% of the road reaches. Hillslope position was an important variable in explaining post-treatment erosion of road reaches. Road reaches that exhibited erosional problems were most commonly found in lower hillslope positions, and both minimal (ripping and draining) and more intensive (export outsloping) road treatments on lower hillslope roads resulted in high sediment yields to streams (660 m^3/km of treated road). In contrast, on upper hillslope positions, all treatment styles worked well and sediment delivery rates were only about 10 m^3/km of treated road. By eliminating the risk of stream diversions and culvert failures, road treatments significantly reduce the long-term sediment risk from abandoned roads.

Adaptive land management involves monitoring the effects of management activities, and modifying land management approaches and techniques based on what is found to be effective. The results of this study can be used to guide future road removal work in the most cost-effective manner. The assessment presented here can also serve as a framework for evaluating the success of other watershed restoration programs. Although erosion rates measured in this study are specific to the site conditions of the Redwood Creek catchment, this approach can be adapted to other regions. Accelerated erosion rates are a widespread problem in many regions of the world, and road treatments can be effective in significantly reducing sediment yields from unpaved roads.

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Appendices

Appendix A

Field Form for Inventory of Roads on Past Watershed Rehabilitation Sites

SITE INFORMATION AND SUMMARY

1. Rehab Project #____________ 2. Work Site #__________
3. Rehab Project Leader______
4. Date Mapped:_____________ 5. Mapped By: ___________________
6. Watershed:_____________________________ 7. Quad ID:__________
8. Site type: [1]Crossing, [2]Landing, [3] Road Reach, [4] Ditch/Road Relief, [5] Skid trail [6] Other
9. Erosion Process: [1]Fluvial (Sec.I) [2]Mass movement (Sec. II) [3] Both [4] None

ROAD INFORMATION

10. Road Name:__________________________________
11. Year of Construction______________ 12. Year of Rehab.__________

CONDITION OF FILL:

13. [1]Intact, [2]Sag, [3]Ponded H_2O, [4]Cracks, [5]Scarps, [6]Holes, [7]Gully/Rills [8] Seeps
14. Fill Failure Potential? [1]Yes, [0]No

REHABILITATION INFO.

15. Primary Treatment [1]Total Outslope, [2]Partial Outslope, [3]Export Outslope [4] Total Excavation [5]Partial Excavation [6]Ripped [7] Drained, [8]Fillsite [9]None [10]Other
16. Secondary Treatment [0] None [1] Rocked Channel [2] Straw Mulch [3] Wattles [4] Check dams [5] Contour Trench [6] Other
17. Top Soil Restored? [1]Yes, [0]No [2] Unknown

Vegetation:

18. Revegetation Treatment: [1] Conifer seedlings, [2]Grass Seed, [3]Willow [4] Alder seed [5]Alder seedlings [6] Other

Existing Vegetation:	Avg. Ht.	Avg. Stem Spacing	RANK
Redwood	19________ft.		20 ________
Douglas Fir	21 ________ft.		22 ________
Alder	23 ________ft.	24_______ft.	25 ________
Tanoak	26________ft.		27________
Madrone	28________ft.		29________
Shrubs	30 ________ft.		31________
Herbaceous-Mesic/Xeric	32 ________% cover		33 ________
Herbaceous-Hydrophytic	34________% cover		35________

36. Exotics present: [1] Foxglove [2] Pampas Grass [3] Scotch Broom [4]Tansy Ragwort [5]Other

SECTION II: MASS MOVEMENT SITE

FEATURE TYPE:

58. [**1**]Earthflow, [**2**]Shallow debris slide, [**3**]Rotational Slump
    [**4**]Debris Torrent, [**5**]Cutbank Failure, [**6**]Fill Failure
    [**7**] Failure of Excavated Fill

SLOPE POSITION AND FORM

59. Hillslope: [**1**] Upper, [**2**] Middle, [**3**] Lower, [**4**] Inner Gorge
60. Topographic: [**1**] Concave, [**2**] Planar, [**3**] Convex
61. BIS? [**1**]Yes, [**0**]No
62. Slope Above_________ %
63. Slope Below_________ %
64. Distance to stream _______ ft.

FEATURE DESCRIPTION

65. Level of Activity: [**1**]Active, [**2**]Waiting, [**3**]Totally Evacuated
66. Average Scarp height:______________ ft.
67. Range of scarp heights:______ ft.
68. Features Present: [**1**]Cracks, [**2**]Scarps, [**3**]Ponded Water,
    [**4**]Sagging, [**5**]Holes, [**6**]Leaning Trees, [**7**]Spring, [**8**]Stream Channel Undercutting, [**9**]Excess H_2O Diverted onto Feature
    [**10**] Buried Wood Exposed

69. **Comments**:

SECTION III: TOTAL EROSION VOLUMES

EROSION VOLUMES FLUVIAL EROSION ON-SITE	Eroded Before Rehab	Excavated in Rehab.	Erosion Since Rehab	Erosion Potential (In 20-yr flood)	I.
Road Fill at Crossing:	70 ____ yd^3	71. ____ yd^3	72. ____ yd^3	73 ____ yd^3	

OFFSITE i.e., from a diversion, or upstream or downstream impacts of crossing failure.

Offsite	74. ____ yd^3		75. ____ yd^3	76. ____ yd^3

II. MASS MOVEMENT

Total Volume-Onsite	77 ____ yd^3	78. ____ yd^3	79 ____ yd^3	80 ____ yd^3
-Offsite	81 ____ yd^3		82 ____ yd^3	83 ____ yd^3

TOTAL VOLUME:

Total Volume Moved:	84 ____ yd^3 (70+74+ 77+81)	85 ____ yd^3 (71+78)	86 ____ yd^3 (72+75+ 79+82)	87 ____ yd^3 (73+76+ 80+83)

Percent Delivery to Channel	88 ____ %	89 ____ %	90 ____ %
Total Yield to Channel	91 ____ yd^3 (% x 84)	92 ____ yd^3 (% x 86)	93 ____ yd^3 (% x 87)

94. Road Type: [1] Cut and Fill [2] Full Bench

Comments: (For example, provide comments on Extreme Erosion: Nature & Likelihood)

DEFINITIONS FOR FORMS

SITE INFORMATION AND SUMMARY

1. Rehab Site #: Obtain from Redwood National Park rehabilitation reports. Usually a 3-digit number with year of rehabilitation listed first: (Example: 80-3)
2. Worksite #: Obtain from Redwood National Park rehabilitation maps. Usually it will be a stream crossing (i.e., RX 4), road reach (RR1) or a landing (L2).
3. Date mapped: The date of your field work
4. Mapped by: The initials (first, middle, last) of those who did the field mapping for this particular site (i.e., MAM)
5. Watershed: This refers to the major tributary to Redwood Creek in which the inventory site is located (i.e, Bridge Creek).
6. Quad ID: Use initials for the appropriate topographic quadrangle, for example:
   BH= Bald Hills, RP = Rogers Peak.
7. Site type: Circle number next to the appropriate item:
   - Crossing: Locations where a road crossed an ephemeral, intermittent or perennial stream.
   - Landing: Locations where logs were stored and loaded onto trucks.
   - Road reach: A length of road that was treated (outsloped, ripped or drained) but without major crossings or landings.
   - Ditch/Road relief - Locations where a culvert used to drain the inboard ditch, or where waterbars and deep ditches presently drain the old road surface.
   - Skid trail - sometimes work was done off the main haul road on smaller skid trails.
   - Other - miscellaneous sites such as rock pits.
8. Erosion Process: Is the erosion at the site caused by running water (fluvial) or a type of landslide (mass movement) or are both types of processes active?
9. Road name - as given by the original timber company, such as the M-7-1 Road.
10: Year of construction: Year(s) the road was constructed. Obtain from Redwood National Park rehabilitation reports or air photos.
11. Year of rehabilitation: Obtain from Redwood National Park rehabilitation reports.
12. Condition of fill: Describe the condition of the road fill at the site by circling all the characteristics or features that are present (can circle more than one item.)

-Intact: Fill is in good shape.

Sag =sagging. Has the edge of the road sagged, but no scarps or cracks are visible? Sagging may mean that scarps or cracks were graded away in the past.

-Pond H20 = ponded water. Are there indications of standing or ponded water at the site?

-Cracks: Are there cracks in the road, suggesting initial stage of road fill failure?

Scarps. Are there scarps in the road with distinct displacement?

Holes. Holes indicate that fill is falling through the crossing, commonly suggesting the presence of decaying logs within the fill.

Gully/rills. Are gullies (greater than 1 ft x 1 ft) or rills (less than 1 ft x 1 ft) present on the road surface or on the fill slope?

13. Fill Failure potential: Yes or no. Does this site have the potential for fill to erode during a large storm (a 20-year storm?)
14. Rehabilitation Information: (May circle more than one item).
    Restoration Technique:
    Total or partial outslope (usually refers to road reaches or landings). In a total outslope the road is recontoured to mimic the natural hillslope, whereas in a partial outslope some road bench remains, and a break in slope between the hillslope and old road surface is obvious.
    Total or partial excavation (usually refers to crossings)-- a total excavation removed fill material down to the original channel, and a partial excavation dished out the crossing but did not go as deep.
    Ripped: when the road was decompacted by rippers mounted on bulldozers. It helps increase infiltration on abandoned logging roads.
    Drained: Large waterbars or cross road drains were constructed to drain water across the old road surface.
    None: Sometimes a segment of road was not treated if it looked stable at the time of rehab. If such segments are now eroding, they get included in this inventory.
15. Top soil restored? During total outsloping, the original topsoil that was removed from the road surface during construction is commonly found and replaced on the road surface. If you can tell by the texture and color of the soil that topsoil was replaced, circle Yes. If the surface material still looks like road fill, answer No. If you can't tell, circle Unknown.
16. Revegetation Treatment: Obtain from Redwood National Park rehabilitation reports. May circle more than one item. "Other" may include alder seeding, jute netting, planting of other species, etc.

17-28: For the existing vegetation, estimate an average height and spacing for the given species, if present. Rank the vegetation types according to dominance with '1' as most common, '2' the next most common, and so on. You only need to rank the top 3 or 4 species. After that, it's often difficult to decide rank.

29-32: Herbaceous: Basically includes everything that isn't a tree or a shrub.
    Mesic/Xeric will include grasses, forbs, ferns, etc.
    Hydrophytic will be those species associated with wet areas and seeps, such as reeds, cattails, horsetails, etc.

Estimate percent cover for herbaceous species: We won't be able to get too accurate here, but we're trying to distinguish between heavy cover with almost no soil showing and sparse, with lots of bare soil.

33. Bedrock type: Get from geology map or field observations.
34. Soil type: Get from Redwood National Park's soil maps.
35. Soil depth: Choose one category based on your field observations in cutbank or streambank exposures.

FLUVIAL EROSION SITE

Always include a sketch on the back of the sheet.

36. Existing erosion feature:

Gully: the site contains a gully as one of the major erosional features. Gullies are new channels that have a cross-sectional area greater than one square foot. Anything smaller is considered a rill and is lumped with surface erosion processes. Gullies are caused by concentrated surface runoff, which often results from stream diversions.

Streambank erosion: The site shows signs of channel widening through erosion of its banks.

Stream incision: The stream has eroded deeper in recent years, usually marked by a distinct break in slope and narrower, incised small channel within a larger channel.

Surface erosion and rilling: Includes rills, sheet erosion, ravelling, soil pedestals, formation of a coarse lag layer on the old road fill surface.

Spring: The crossing area or excavation site drains a spring or seep, which is causing erosion downslope.

Channel Description:

37. Grade of crossing: Measure longitudinal gradient of excavated crossing with a clinometer.

38, 39. Do the same for the natural channel upstream and downstream of the excavated area.

40. Channel width at crossing: What is the estimated width at high flow in the excavated crossing?

41, 42, What is the average channel width upstream and downstream of the excavated crossing?

43: Length of excavated crossing: Measure length from upslope side to downslope side of excavation.

44. Total drop: This is the elevation difference between the downslope side of the excavation and the upslope side.

45. Drop due to wood: Frequently logs or other woody debris cause a small waterfall in the channel. These are sites where much energy is dissipated. Total the elevation drop for all the wood-based steps in the excavated channels. For example, two log steps, both 2 ft. high, would yield a total "drop due to wood"of 4 ft.

46. Drop due to rocks. Similar to 45, but in this case the channel 'steps' are due to boulders or bedrock in the channel bed, causing plunge pools.

47. Dominant bed material: Circle one that best describes the bed material in the channel bottom. Sand is less than 2 mm. P/C = pebbles and cobbles, between 2 mm and 256 mm, Boulders are particles greater than 10 inches median diameter (256 mm). SmOD is small organic debris (< 6 inches in diameter) and LrgOD is large organic debris (> 6 inches in diameter).

48. High Bedload. Subjective assessment if a lot of sand, pebbles and cobbles have been transported through this channel. If there's a lot of moss growing on boulders, it's probably an indication that not much bedload has been transported recently.

49. Diversion Potential. Does the site have the potential for flow to be diverted from its natural flow course as a result of conditions at this site? The most probable conditions for diversion potential are when the channel is not well incised and the old road grade is steep.

50. Is the stream currently diverted from its natural flow course at this site?

51. Comments: These are useful to explain numbers, and discuss other features that aren't mentioned on this form.

SECTION II - MASS MOVEMENT SITE

Feature type: Circle those that apply:

Earthflow: An earthflow is a slow moving, deep seated landslide with an irregular and hummocky surface.

Shallow debris slide: A debris slide moves translationally along planar or gently undulating surfaces. The head scarp is near vertical, and cracks parallel to the slope are usually present in the crown region. Blocks break up into smaller and smaller parts as the slide moves toward the toe. Movement is relatively slow as compared to a debris torrent, but rapid in comparison to an earthflow. If forested, trees will appear jack-strawed or have curved trunks.

Rotational slump: This feature involves movement of a block, or series of blocks, such that displacement is along a concave upward surface. These features are characterized by steep head scarps, and contain flanks with scarps which decrease in height from the head region to the toe. The upper surface of the blocks are either flat or tilted back into the hillslope, and may contain trees leaning upslope. Often the movement grades into a more translational nature toward the lower portion of the slump which may contain a zone of uplift, and trees leaning downslope.

Debris torrent. This is an extremely rapid downslope movement of material due to complete saturation. A failed surface contains a serrate or V-shaped scarp, and irregular flanks often with levees in the lower portions. Displacement occurs along a planar surface, and the surface scar is long and narrow. Debris torrents typically follow drainage routes, scouring the channel valley to bedrock and mobilizing soil and trees. They typically build up sufficient energy during failure such that the liquefied material accumulates only at sharp breaks in stream valley slope or orientation.

Cutbank - feature is a failed or slumped cut bank on an old road.

Fill failure - Feature involves perched fill from a road or landing that is failing or has failed downslope.

Failure of excavated fill: This is the case where the road fill material that was excavated moved, and set on the slope (outsloped or put on a fillsite) has subsequently failed since the rehab project was completed.

SLOPE POSITION AND FORM

Circle the responses that define the site's local position on the hillslope, not its position relative to the entire basin. It is the position of the road from the ridge top to the closest high order channel. It's helpful to have a topo map with you for this determination.

Upper hillslope area. Is this site within the upper one-third of the slope?

Middle hillslope area. Is this site within the middle one-third of the slope.

Lower hillslope area. Is this site within the lower one-third of the slope?
Inner Gorge: Is the site located within the steep side slopes of an inner gorge of a stream channel. (Usually > 65% slope).

Topographic Form: Circle one. The general shape of the affected hillslope is best described as:
Concave: Convergent (spoon shaped, or a hollow)
Planar. Straight
Convex: Divergent, such as the nose of a ridge, watershed divide or interfluve.
BIS. Break in Slope. Is the site located at or immediately above a distinct change in hillslope gradient (BIS) which leads from either: moderate slopes above the feature to steeper slopes below, or steeper above and gentler below?
Slope Above (%). The average hillslope gradient immediately upslope of the site. This question is optional due to the time that may be involved in obtaining a measurement because of brush, etc.
Slope Below (%). The average gradient immediately downslope of the site. This question is optional due to the time that may be involved in obtaining a measurement if brush is too thick.
Distance to stream (ft) Indicate the approximate distance to the nearest stream from the toe of the feature.
Comments: Include any other information that you think is pertinent here.

FEATURE DESCRIPTION

Level of Activity: Circle best answer.

Active: Is the site active (movement within the last several years?) "Active" means the erosion is still occurring, though not necessarily at the original rate. Gullies will have near vertical, raw banks and/or active headcuts. Landslides will show recent, mostly bare scarps, recently titled trees and perched blocks which have just started to move.

Waiting: Features assigned this classification are thought to be currently inactive (no signs of movement in the last several years), but the scarps and other indicators suggest that during an especially large storm the instability could become active and fail or move downslope. This feature type also includes sites which show subtle indicators of future mass movement, but which have not yet moved significantly.

Totally Evacuated. Has the material associated with the site been completely remove?

Average scarp height: What is the average scarp height in feet?
Range of scarp heights: What is the range of scarp heights in feet?

Features present: CIRCLE ALL THAT APPLY.
-Cracks. Are there cracks in the road or ground, suggesting slope movement?
-Scarps. Are there scarps in the road or ground with distinct displacement?

-Ponded Water: Are there indications of standing or ponded water at the site, if not now, during the wet season?
-Sagging. Has the edge of the road sagged, but no scarps or cracks are visible. Sagging may mean that scarps or cracks were graded away in the past.
-Holes. Holes indicate that fill is falling through the crossing, often suggesting the presence of decaying logs within the fill.
-Leaning trees. Does the unstable are have leaning or bowed trees?
-Spring: Is the mass movement feature a result of emergent ground water? Cut banks associated with road building occasionally intersect ground water flow, which if not managed properly can lead to erosion.
-Stream channel undercutting: Is the site be destabilized (or has the potential for being destabilized) by stream channel undercutting?
-Excess water diverted onto feature. Excess water diverted onto a site can initiate failure and /or accelerate erosion. Is upslope water diverted to this site? Is water ponded (in an inboard ditch or poorly drained surface) on the site, causing saturation, which may lead to failure.

SECTION III - TOTAL EROSION VOLUMES

There are four time periods to consider here.
The first time period involves how much erosion occurred before the rehabilitation work was done. You'll have to read the old reports and study their maps to try to figure this one out, and on some sites you will have no information. The 1978 air photos may help you in some cases.
Excavated in rehab: This is the volume of material excavated from a stream crossing or removed from a landslide during the actual rehabilitation work. Again, you'll need to read the old rehab reports to get a volume excavated, and this information may not always be available.
Erosion since rehab: This is the amount you'll be measuring in the field based on what you think the ground configuration was after rehab and what has eroded since (in gullies, slumps, incised channels, etc.)
Erosion potential: This is your estimate, based on your field observations, of how much material will eroded during the next 20 years, assuming a large (20-year storm) occurring during this period. Perched fill, cracks in the fill, undercut or oversteepened banks, are some indicators of potential erosion. Consider all site conditions and past erosion processes evident within the basin in similar geomorphic, hydrologic, and soil settings in deciding the potential.

The total volume moved (eroded or excavated) is the sum of fluvial-onsite, fluvial-off-site and mass movement features.

Percent delivery to channel. Estimate the percent of eroded material that entered in the past and will enter in the future to the nearest stream.

Total yield to channel: This is the total volume moved times the delivery percentage. This is the amount of sediment you think will actually make it to a stream channel in the time periods defined above.

Comments: Add any other comments on the site here. If you think there is a great potential for a large amount of erosion to occur in the next 20 years at this site, say so and explain why you think you. Sketches are always helpful. Use additional paper if necessary.

Appendix B: Statistical Analysis

Forty one-mile long road segments were selected randomly for field mapping, but two segments, later deemed inaccessible, were not surveyed. During the field mapping phase each road segment was further subdivided into 'stream crossings' where a culvert or drainage structure had been removed, and intervening 'road reaches' which were treated by a variety of methods. Geomorphic maps that were constructed when the roads were first treated were used to supplement field observations in order to reconstruct site conditions at the time of treatment. Each sampled road segment (one mile long) comprised several treatment sites, representing both stream crossings and road reaches along that segment. Consequently, the inventory of 38 segments of treated roads (61 km) resulted in a data set consisting of 207 crossings and 301 road reaches. Mean crossing length was 26 m ($\pm$ 17 m) and mean road reach length was 116 m ($\pm$ 84 m). Each excavated stream crossing and treated road reach had a separate inventory form with pertinent site information, map and erosion measurements.

Several types of post-road removal erosion were measured: mass movement, bank erosion and channel incision, and gullying. The inventory form used at each site is shown in Appendix A. Because previous studies had shown surface erosion from treated roads delivered a small proportion of the total sediment in this catchment (Kveton and others, 1983), surface erosion on the treated road bench or crossing was not measured. Sediment delivery was estimated by measuring the void left by bank erosion or mass movement features and measuring the dimensions of the downslope deposit, if present. Commonly, the toe of the landslide entered a stream channel, and the eroded material had been transported from the site by the time of the field mapping. The minimum size of gully measured was 0.1 m^2 in cross-sectional area. Type and density of vegetation on the site were also recorded. Many road reaches were thickly vegetated, which obscured small post-treatment erosion scars.

Factors used in the analysis of erosion and sediment delivery from treated road reaches were: hillslope position (upper, mid-slope, or lower); bedrock (schist, sandstone, or other); treatment type (ripped and drained, partial outslope, total outslope, export outslope or fill site); time period of restoration activity (1980-1983, 1984-1987, 1988-1991, and 1992-1996); and hillslope curvature (convex, planar, or concave). For stream crossings, the factors used were: bedrock type, date of treatment, drainage area, channel gradient, volume excavated from channels, step frequency and elevation drop due to steps.

Because road reach boundaries were based on the spacing between stream crossings, road reaches were of unequal length. Consequently, erosion from road reaches was normalized by the length of road reach (m^3/m of road). In contrast, crossing erosion was expressed as 'm^3 eroded per excavation.' It might also be preferable to express channel erosion volumes as a normalized value (m^3/m of channel), but in the field it was difficult to accurately determine the length of the excavated channel. Post-treatment channel adjustment upstream and downstream of the excavated channels blurred the boundaries of the excavated channel, and in many sites post-treatment erosion extended beyond the limits of the crossing excavation itself.

The treatment method for stream crossings (removal of culverts and reshaping streambanks) differed from that of road reaches (decompacting, draining or recontouring the road bench). Also, fluvial erosion (channel incision and bank erosion) caused most post-treatment erosion in excavated stream crossings, whereas mass movements accounted for three-fourths of the erosion from road reaches. For these reasons, the analysis considered data for stream crossings separately from road reaches.

The explanatory variables used in the regression analyses are not necessarily independent. For example, the treatment technique of ripping and draining was more commonly used in the early time period of 1980 to 1983, than in later periods (Figure 9a). Another confounding factor is that the roads considered the most unstable were treated early in the program (Figure 9b). Contingency tables were used to check for independence among the variables, and several interaction terms were tested for significance in the regression analyses. Step-wise logistic regression with forward selection, including interaction variables, was used to determine which variables to include in the most reasonable regression model for erosion on road reaches.

The total amount of material eroded from treated road reaches was 25,900 m^3. Most (77%) of this erosion was attributed to mass movement processes, primarily road fill failures. Of the total erosion from road reaches, 74% of the eroded material was delivered to a stream channel. Most treated road reaches performed well and produced very little sediment. The cumulative distribution of erosion from road reaches in even more highly skewed than that for road crossings (Figure 10b). Twenty percent of the treated road reach length produced 99% of the total erosion from treated road reaches. Total post-treatment erosion from 61 km of road, including both fill failures and stream crossing erosion, was 37,000 m^3 (600 m^3/km of road); total sediment delivery was 29,500 m^3 (480 m^3/km of road).

A logistic regression model, based on 'erosion' or 'no erosion' of the treated road sites, resulted in four significant explanatory variables: hillslope position ($p = 0.0017$), date of treatment ($p = 0.0107$), treatment type ($p = 0.0181$), and an interaction term (hillslope position * treatment type) ($p=0.0280$). The results of the logistic regression can be expressed by the odds of failure (that is, erosion occurred on the road reach). The odds of failure of roads treated in the early part of the program (1980-1983) were 6.8 times greater than the odds of failure for roads treated later (1992-1996). Similarly, the odds of failure for roads in lower hillslope positions were 51.3 times those of upper hillslope roads, and the odds of failure for mid-slope roads were 5.3 times those of upper slope roads.

Although the model was significant at the 99% confidence level, the percentage of deviance explained by the model is only 16%. Erosion on treated road reaches was highly variable, as it was for treated stream crossings. Besides the geomorphic variables considered in this analysis, road reach erosion is also influenced by site specific conditions, such as the presence of seeps, depth to bedrock or a history of past mass movement activity. Even though bedrock type was not a significant variable in this regression model, a finer distinction of bedrock based on the degree of fracturing, shearing and erodibility in individual units may be worth exploring in the future.

Table 6: Estimated odds ratios from logistic regression model relating post-treatment erosion on road reaches to date of treatment, hillslope position, type of treatment, and an interaction term.

Date of Treatment (p = 0.008)	Estimated Odds Ratio	**(Hillslope Position * Treatment)** (p = 0.006)*	Estimated Odds Ratio
1980-1983	6.7	Upper: Ripped and Drained	1.0
1984-1986	3.5	Upper: Partial Outslope	2.6
1987-1991	1.8	Upper: Total Outslope	7.0
1992-1996	1.0	Upper: Fill	0.0
Hillslope Position (p = 0.007)		Middle: Ripped and Drained	1.0
Upper	0.2	Middle: Partial Outslope	0.0
Middle	0.6	Middle: Total Outslope	0.8
Lower	1.0	Middle: Fill	0.3
Treatment (p = 0.052)		Lower: Ripped and Drained	1.0
Ripped and Drained	2.0	Lower: Partial Outslope	0.1
Partial Outslope	0.3	Lower: Total Outslope	0.1
Total Outslope	1.4	Lower: Export Outslope	0.2
Export Outslope	2.3	Lower: Fill	0.2
Fill	1.0		

* Results from (Upper* Export Outslope) and (Middle*Export Outslope) were not included because there were < 5 samples in each category.

In contrast to road reaches, 96% of treated stream crossings exhibited detectable levels of erosion (although most channel adjustment was minor). The entire length and width of the excavated channel were surveyed, so detection of erosion was not a problem. In this case, standard multiple regression techniques were applied. An interaction term included in the regression analysis was (drainage area * channel gradient), a surrogate for stream power. Step-wise regression with forward selection, using an F-to-enter of 4, determined which variables to include in the final regression model.

Channel incision and bank erosion were the most common forms of post-treatment erosion in crossings. To determine a relationship between site characteristics and post-treatment erosion, many variables were used in the forward selection regression procedure (channel gradient, drainage area, stream power, volume excavated during treatment, bedrock, date of treatment, frequency of boulder and log steps, and percent vertical drop due to steps). Only two explanatory variables were significant in the best-fit regression model:

$$\text{Volume eroded } (m^3) = 20.8 + 0.041 \text{ (stream power)} + 0.009 \text{ (volume excavated, } m^3\text{)}$$

The surrogate for stream power (drainage area * channel gradient) ($p =< 0.0001$) and the volume of material excavated from a channel during treatment ($p = 0.0085$) were significant variables in explaining the volume of post-erosion in excavated stream channels. The greater the stream power and the larger the excavation, the more the channel eroded following treatment. Deeply incised channels that required more fill to be excavated were more vulnerable to post-treatment erosion than shallow crossings with less road fill because the reshaped streambanks were steeper and more likely to fail.

The regression model was statistically significant at the 99% confidence level; however, the fitted model only explains 18% of the variability in post-treatment erosion. Erosion following treatment is highly variable, and many site-specific conditions (such as the presence of bedrock, springs, or poorly drained soils or incomplete excavations) can influence post-treatment erosion as well.