Evaluating the Impacts of Logging Activities on Erosion and Suspended Sediment Transport in the Caspar Creek Watersheds[1]

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Abstract: *Suspended sediment has been sampled at both the North and South Fork weirs of Caspar Creek in northwestern California since 1963, and at 13 tributary locations in the North Fork since 1986. The North Fork gaging station (NFC) was used as a control to evaluate the effects of logging in the South Fork, in the 1970's, on annual sediment loads. In the most conservative treatment of the data, suspended loads increased by 212 percent over the total predicted for a 6-yr period commencing with the onset of logging. When the roles of the watersheds were reversed and the same analysis repeated to evaluate harvesting in the North Fork under California Forest Practice Rules in the 1990's, no significant increase was found at NFC in either annual suspended or bed load.*

With the advent of automatic pumping samplers, we were able to sample sediment concentration much more frequently in the 1980's. This allowed storm event loads from control watersheds in the North Fork to be used in a new regression analysis for NFC. According to this more sensitive analysis, for the 7-yr period commencing with the onset of logging, the sum of the suspended storm loads at NFC was 89 percent higher than that predicted for the undisturbed condition. The much greater increase after logging in the South Fork is too great to be explained by differences in sampling methods and in water years, and appears to be the result of differences in road alignment, yarding methods, and stream protection zones.

Similar analyses of storm event loads for each of the treated subwatersheds in the North Fork suggested increased suspended loads in all but one of the tributaries, but effects were relatively small or absent at the main stem locations. Of watersheds with less than 50 percent cut, only one showed a highly significant increase. The greater increase in sediment at NFC, compared to other main-stem stations, is largely explained by a 3,600-m^3 landslide that occurred in 1995 in a subwatershed that drains into the main stem just above NFC. Differences among tributary responses can be explained in terms of channel conditions.

Analysis of an aggregated model simultaneously fit to all of the data shows that sediment load increases are correlated with flow increases after logging. Field evidence suggests that the increased flows, accompanied by soil disruption and intense burning, accelerated erosion of unbuffered stream banks and channel headward expansion. Windthrow along buffered streams also appears to be important as a source of both woody debris and sediment. All roads in the North Fork are located on upper slopes and do not appear to be a significant source of sediment reaching the channels.

The aggregated model permitted evaluation of certain types of cumulative effects. Effects of multiple disturbances on suspended loads were approximately additive and, with one exception, downstream changes were no greater than would have been expected from the proportion of area disturbed. A tendency for main-stem channels to yield higher unit-area suspended loads was also detected, but after logging this was no longer the case in the North Fork of Caspar Creek.

Soil erosion and mass movement play major roles in shaping the landscapes that surround us. These processes complement those that build mountains and soils, resulting in landforms such as valleys, ridges, stream channels, and flood plains. Human activities that change the balances between these processes can have consequences that are detrimental to humans and the ecosystems we depend on. Human activities often lead to an acceleration of soil movement, net soil losses from hillslopes, and increases in sediment transport and deposition in stream channels. When soil erosion and mass movement directly damage roads, bridges, and buildings, the costs are immediate and obvious. Direct effects on ecosystem function and site productivity are also serious issues in many areas. Indirect impacts on downstream water quality and stream channel morphology, however, are often of greater concern.

Sediment-laden water supplies reduce the capacity of storage reservoirs and may require additional treatment to render the water drinkable. Sediment in irrigation water shortens the life of pumps and reduces soil infiltration capacity. Water quality is also an important issue for recreational water users and tourism.

Impacts of water quality on fish and aquatic organisms have motivated much of the research being presented at this conference. High sediment concentrations can damage the gills of salmonids and macroinvertebrates (Bozek and Young 1994, Newcombe and MacDonald 1991). High turbidity can impair the ability of fish to locate food (Gregory and Northcote 1993) and can reduce the depth at which photosynthesis can take place. However, suspended sediment is not always detrimental to fish, and indexes based on duration and concentration are unrealistically simplistic (Gregory and others 1993). Turbidity, can, for example, provide cover from predators (Gregory 1993).

If stream channels cannot transport all the sediment delivered from hillslopes, they will aggrade, resulting in increased risks for overbank flooding and bank erosion. It was this sort of risk, threatening a redwood grove containing the world's tallest tree, that motivated the expansion of Redwood National Park in 1978 (U.S. Department of Interior 1981). Accelerated delivery of sediment to streams can result in the filling of pools (Lisle and Hilton 1992), and channel widening and shallowing. Hence, fish rearing habitat may be lost, and stream temperatures often increase. Excessive filling in spawning areas can block the emergence of fry and bury substrates that support prey organisms. Settling and infiltration of fine sediments into spawning gravels reduces the transport of oxygen to incubating eggs (Lisle 1989) and inhibits the removal of waste products that accumulate as embryos develop (Meehan 1974). If aggradation is sufficient to locally eliminate

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surface flows during the dry season, fish can lose access to good upstream habitat or become trapped in inhospitable environments.

How Do Harvest Practices Affect Sediment Movement?

Figure 1 displays some of the mechanisms linking harvest activities with instream sediment transport. It is impossible to show all the potential interactions in only two dimensions, but the figure does hint at the complexity of controls on sediment movement. Timber harvest activities can accelerate erosion primarily through felling, yarding, skidding, building and using roads and landings, and burning.

Felling

Removing trees reduces evapotranspiration and rainfall interception, thus resulting in wetter soils (Keppeler and others 1994, Ziemer 1968). Loss of root strength and wetter soils can decrease slope stability (O'Loughlin and Ziemer 1982, Ziemer 1981). Trees near clearcut edges face increased wind exposure and become more susceptible to blowdown (Reid and Hilton, these proceedings), disrupting soils if trees become uprooted. Addition of woody debris to channels can cause scouring of the banks and channel, but also can reduce sediment transport by increasing channel roughness and trapping sediment (Lisle and Napolitano, these proceedings). The effects of felling upon erosion can be altered by controlling the quantity and the spatial and temporal patterns of cutting.

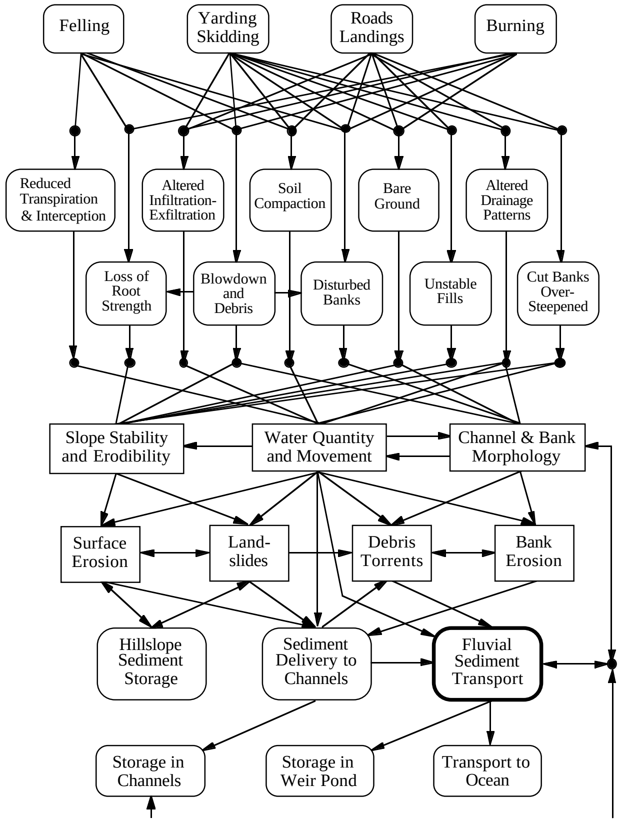

Figure 1—Conceptual diagram showing the major pathways through which logging activities influence fluvial sediment transport.

Yarding and Skidding

Heavy equipment compacts soils, decreasing infiltration and percolation rates and increasing surface water. If vegetation and duff are removed, the underlying soils become vulnerable to surface erosion. The pattern of yarding and skidding can alter drainage paths and redirect water onto areas that may be more likely to erode than naturally evolved channels. Damage from yarding and skidding is controlled primarily by the type of equipment, the care exercised by the equipment operator, timing of operations, landing location, and yarding direction.

Roads and Landings

Roads and landings have similar, but usually more pronounced, impacts as yarding and skidding, and their presence can greatly increase landslide risk. Compaction of the road bed can impede subsurface drainage from upslope areas, resulting in increased pore water pressures (Keppeler and Brown, these proceedings). Road cuts and fills are vulnerable to accelerated runoff and surface erosion, and are particularly vulnerable to slumping, especially on steep slopes or if the fill or sidecast material has not been properly compacted. Although roads and landings may be only a small part of the total forest area, they are responsible for a disproportionate amount of the total erosion (McCashion and Rice 1983, Swanson and Dyrness 1975), often more than half. The erosional impact of roads and landings can be managed through road alignment, design and construction, drainage systems, type and timing of traffic, and maintenance.

Burning

Burning can increase erodibility by creating bare ground, and hot burns can delay revegetation by killing sprouting vegetation. In some cases, burning can accelerate revegetation by releasing or scarifying seeds and preparing a seed bed. Burning in areas with sandy soils can create water-repellent soils and increase surface runoff (DeBano 1979). The effect of burning on erosion depends primarily on the temperature of the burn, soil cover, and soil and vegetation types. Soil moisture, wind, air temperature, humidity, slope steepness, and fuel abundance and distribution are the major factors affecting burn temperatures.

Site Factors

Some sites are particularly vulnerable to mass wasting, and these sites, while occupying a small part of the landscape, have been found to be responsible for a large proportion of the total erosion in northwestern California (Dodge and others 1976, Rice and Datzman 1981). In the Critical Sites Erosion Study, an evaluation of 157 mass failure sites (>153 m^3) and 326 randomly selected control sites from logged areas in northwestern California, Durgin and others (1989) concluded that management and site factors played an equal role in road failures. In contrast, management factors were secondary to site factors on hillslopes. The primary site factors associated with mass failures were steep slopes, noncohesive soils and fill materials, and incompetent underlying regolith. Most failures were associated with the concentration of subsurface water, as evidenced by perennial seeps, poorly drained soils, phreatic vegetation, and locations in swales, inner gorges, and lower slope positions. Previous slope failures were also evident at many of the sites. The primary management factors associated with mass failures were steep or overloaded fill slopes, steep cut banks, and inadequate maintenance of roads and drainage systems. A field procedure for estimating the probability of mass failure was also developed (Lewis and Rice 1990, Rice and Lewis 1991) from the Critical Sites Erosion Study.

Connecting Forest Practices with Water Quality

It is often difficult to identify the causes of erosion. Factors such as increased soil water or reduced root strength are not directly observable. Landslides are normal, stochastic, geomorphic events in many undisturbed areas. Therefore, it may be impossible to show that a landslide in a logged area would not have occurred had the area been treated differently.

There is usually a great deal of uncertainty in determining when and how much sediment from an erosion feature was delivered to a stream channel. And it is even more difficult to determine the origin of suspended sediment that has been measured at a gaging station.

Hence, many studies are correlative and rely on statistics to identify relations between disturbance and water quality. In environmental research, it is difficult to execute an experimental design that permits wide inference. The best designs require randomly assigning the treatments of interest to a large number of similar experimental units. The random assignment reduces the likelihood of associations between treatments and characteristics that might affect the response of some subset of experimental units. When studying a highly variable response such as sediment transport, large sample sizes are needed to detect changes even when the changes are substantial.

When the experimental unit is a watershed, it is usually impractical to randomly assign treatments or monitor a large number of watersheds. Instead, we use watersheds with similar physical characteristics and subject to similar environmental influences, and we repeat measurements before and after treatments are applied, maintaining at least one watershed as an untreated control throughout the study. If the relationship between measurements in the treated and control watersheds changes after treatment, then we can reason that the change is probably due to the treatment, unless some chance occurrence (unrelated to the treatments) affected only one of the watersheds. In reality, we have little control over such chance occurrences. For example, there is no guarantee that rainfall intensities will be uniform over the entire study area.

Such a paired-watershed design can provide a basis for concluding whether a change occurred (Chow 1960, Wilson 1978) and can be used to estimate the magnitude of changes. If chance occurrences can be eliminated, effects can be attributed to the *overall* treatment. If multiple watersheds are included in the design, it may be useful to relate the magnitude of response to disturbances such as proportion of area logged, burned, compacted by tractors, etc. But, without additional evidence, nothing can be concluded about specific causative mechanisms. Conclusions should be *consistent* with the statistical evidence, but cause and effect must be inferred non-statistically, by relating the results to concurrent studies of other responses and physical processes, field observations, and similar observations made elsewhere by others.

Study Area

The Caspar Creek Experimental Watersheds are located about 7 km from the Pacific Ocean in the Jackson Demonstration State Forest, Mendocino County, California (Preface, fig. 1, these proceedings). Until the 1970's, both the 424-ha South Fork and 473-ha North Fork watersheds were covered by second-growth redwood forests, originally logged between 1860 and 1904. Both watersheds are underlain by sandstones and shales of the Franciscan assemblage. Rainfall averages about 1,200 mm yr^{-1}, 90 percent of which falls during October through April, and snow is rare. The location, topography, soils, climate, vegetation, and land use history are described in detail by Henry (these proceedings). The geology and geomorphology are described by Cafferata and Spittler (these proceedings).

Methods

South Fork Treatment

The South Fork of Caspar Creek was roaded in the summer of 1967 and selectively logged in 1971-1973, before Forest Practice Rules were mandated in California by the Z'Berg Nejedly Forest Practice Act of 1973. About 65 percent of the stand volume was removed. In contrast with later logging in the North Fork, 75 percent of the roads in the South Fork were located within 60 m of a stream, all yarding was done by tractor, ground disturbance amounted to 15 percent of the area, and there were no equipment exclusion zones. Details are provided by Henry (these proceedings) and by Rice and others (1979). The North Fork was used as a control watershed to evaluate the effects of logging in the South Fork until the North Fork phase of the study was begun in 1985.

North Fork Treatments

The subwatershed containing units Y and Z (Preface, fig. 2, these proceedings) of the North Fork was logged between December 1985 and April 1986. At the time, this area was thought to have different soils than the remainder of the North Fork, so it was omitted from the study plan that specified logging would begin in 1989. The remainder of the North Fork logging took place between May 1989 and January 1992. Three subwatersheds (HEN, IVE, and MUN) were left uncut throughout the study for use as controls. Henry (these proceedings) summarizes the logging sequence. Briefly, 48 percent of the North Fork (including units Y and Z) was clearcut, 80 percent of this by cable yarding. Tractor yarding was restricted to upper slopes, as were haul roads, spur roads, and landings. Ground disturbance from new roads, landings, skid trails, and firelines in the North Fork amounted to 3.2 percent of the total area. Streams bearing fish or aquatic habitat were buffered by selectively logged zones 23-60 m in slope width, and heavy equipment was excluded from these areas.

Suspended Sediment and Turbidity Measurements

Accurate suspended sediment load estimation in small rain-dominated watersheds like Caspar Creek depends upon frequent sampling when sediment transport is high. Sediment concentrations are highly variable and inconsistently or poorly correlated with water discharge (Colby 1956, Rieger and Olive 1984). Since the 1960's, manual sampling methods have been standardized by the U.S. Geological Survey. However, adequate records are rare because it is inconvenient to sample at all hours of the night and weekends. Errors of 50-100 percent are probably typical when sampling is based on convenience (Thomas 1988, Walling and Webb 1988).

In the South Fork phase of the study from 1963 to 1975, sediment sampling was semi-automated by rigging bottles in the weir ponds at different heights. These *single-stage samplers* (Inter-Agency Committee on Water Resources 1961) filled at known stages during the rising limb of the hydrograph, but the much lengthier falling limb was sampled using DH-48 depth-integrating hand samplers (Federal Inter-Agency River Basin Committee 1952) and, in most cases, was not well-represented. In 1974 and 1975, the number of DH-48 samples was increased greatly and, in 1976, the single-stage samplers were replaced by pumping samplers. The average number of samples collected was 58 per station per year in 1963-1973 and 196 per station per year in 1974-1985.

During the North Fork phase of the study, in water years 1986-1995, the North Fork weir (NFC), the South Fork weir (SFC) and 13 other locations in the North Fork were gaged for suspended sediment and flow (Preface, fig. 2, these proceedings). Pumping samplers were controlled using programmable calculators and circuit boards that based sampling decisions on real-time stage information (Eads and Boolootian 1985). Sampling times were randomly selected using an algorithm that increased the average sampling rate at higher discharges (Thomas 1985, Thomas 1989). Probability sampling permitted us to estimate sediment loads and the variance of those estimates without bias. We also sent crews out to the watershed 24 hours a day during storm events to replace bottles, check equipment, and take occasional, simultaneous, manual and pumped samples. The average number of samples collected in 1986-1995 was 139 per station per year.

In water year 1996, we began using battery-operated turbidity sensors and programmable data loggers to control the pumping samplers at eight gaging stations, and monitoring was discontinued at the remaining seven stations. Although turbidity is sensitive to particle size, composition, and suspended organics, it is much better correlated with suspended sediment concentration than is water discharge. A continuous record of turbidity provides temporal detail about sediment transport that is currently impractical to obtain by any other means, while reducing the number of pumped samples needed to reliably estimate sediment loads (Lewis 1996). However, because these turbidity sensors remain in the stream during measurement periods, they are prone to fouling with debris, aquatic organisms, and sediment, so it was still necessary to frequently check the data and clean the optics. The average number of samples collected in 1996 was 49 per station per year.

Suspended Sediment Load Estimation

The basic data unit for analysis was the suspended sediment load measured at a gaging station during a storm event or hydrologic year. Annual loads were estimated only for NFC and SFC and, to facilitate comparisons with the South Fork study, these were computed by Dr. Raymond Rice using the same methods as in an earlier analysis (Rice and others 1979). This involved fitting sediment rating curves by eye, multiplying the volume of flow in each of 19 discharge classes by the fitted suspended sediment concentration at the midpoint of each class, and summing. As technology has improved over the years, our methods of sample selection have improved. Thus, although the computational scheme for estimating annual loads was repeated in both studies, the sampling bias has changed, and caution must be used when comparing the sediment loads from the two studies.

For estimating storm loads in 1986-1995, the concentrations between samples were computed using interpolations relating concentration to either time or stage. Concentration was first adjusted to obtain cross-sectional mean concentrations using regressions based on the paired manual and pumped samples. For those events in which probability sampling was employed, loads and variances were also estimated using appropriate sampling formulae (Thomas 1985, Thomas 1989). However, Monte Carlo simulations (Lewis and others 1998), showed that the interpolation methods were more accurate (lower mean square error). Based on the variance estimates and simulations, the median error of our estimates for storm events was less than 10 percent.

For estimating storm loads in 1996, concentration was predicted using linear regressions, fit to each storm, of concentration on turbidity. This method produced load estimates with the same or better accuracy than before, while substantially reducing the number of samples collected (Lewis 1996). Time or stage interpolation was employed for periods when turbidity information was unavailable.

Total Sediment Load Estimation

The bedload and roughly 40 percent of the suspended load settle in the weir ponds, and thus are not measured at NFC and SFC. The weir ponds are surveyed annually to estimate total sediment load (suspended plus bedload) by summing the pond accumulations and sediment loads measured at the weirs. Pond volumes are converted to mass based on a density of 1,185 kg m^{-3}. In some of the drier years of record (1972, 1976, 1987, 1991, 1992, and 1994), negative pond accumulations have been recorded. These values may result from settling or measurement errors, but some of the values were too large in magnitude to have resulted from settling alone, so negative values were converted to zero before adding pond accumulations to suspended loads. In the results below, only those that explicitly refer to *total* sediment load include any sediment that settled in the weir ponds.

Erosion Measurements

Starting in 1986, a database of failures exceeding 7.6 m^3 (10 yd^3) was maintained in the North Fork. This inventory was updated from channel surveys at least once a year. Road and hillslope failures were recorded when they were observed, but an exhaustive search was not conducted. Volume estimates were made using tape measurements of void spaces left by the failures, except in a few cases where more accurate survey methods were used. For each failure, crews recorded void volume, volume remaining at the site (starting in 1993), location, distance to nearest channel, and any association with windthrow, roads, or logging disturbance.

Discrete failures such as those included in the failure database are relatively easy to find and measure. In contrast, surface erosion is difficult to find and sample because it is often dispersed or inconspicuous. To obtain an estimate of dispersed erosion sources, erosion plots were randomly selected and measured in each subwatershed. Rills, gullies, sheet erosion, and mass movements were measured on independent samples of road plots and 0.08-ha circular hillslope plots. Road plots consisted of 1.5-m wide bands oriented perpendicular to the right-of-way, plus any erosion at the nearest downslope diversion structure (water bar, rolling dip, or culvert). A total of 175 hillslope plots and 129 road plots were measured. These data were collected for a sediment delivery study and are summarized in a separate report by Rice (1996).

Analyses and Results

Annual Sediment Loads after Logging the South Fork

Linear regressions between the logarithms of the annual suspended sediment loads at the two weirs were used to characterize (1) the relationship of SFC to NFC before the 1971-1973 logging in the South Fork and (2) the relationship of NFC to SFC before the 1989-1992 logging in the North Fork.

The calibration water years used in the South Fork analysis were 1963-1967, before road construction. The sediment load in 1968, after road construction, did not conform to the pretreatment regression (*fig. 2a*), but the data from the years 1969-1971 were not significantly different from the 1963-1967 data (Chow test, $p = 0.10$). In 1968, the increase in suspended load was 1,475 kg ha^{-1}, an increase of 335 percent over that predicted for an undisturbed condition. The years 1972-1978 (during and after logging) again differed from the pretreatment regression. Water year 1977 was missing owing to instrument malfunction. By 1979, the suspended sediment load at SFC had returned to pretreatment levels. The increased suspended load after logging amounted to 2,510 kg ha^{-1}yr^{-1}, or an increase of 212 percent over that predicted for the 6-yr period by the regression. (Predictions were corrected for bias when backtransforming from logarithms to original units.) The greatest absolute increases occurred in the years 1973 and 1974, followed by 1975 (*fig. 2b*).

A pair of large landslides (one in each watershed) occurred during hydrologic year 1974, complicating the analysis by Rice and others (1979), where the North Fork's sediment load was adjusted downward because most of the North Fork slide reached the stream, while most of the South Fork slide did not. However, that year did not appear anomalous in my analysis, and I did not make any adjustments. But the unadjusted prediction requires extrapolation of the regression line well beyond the range of the pretreatment

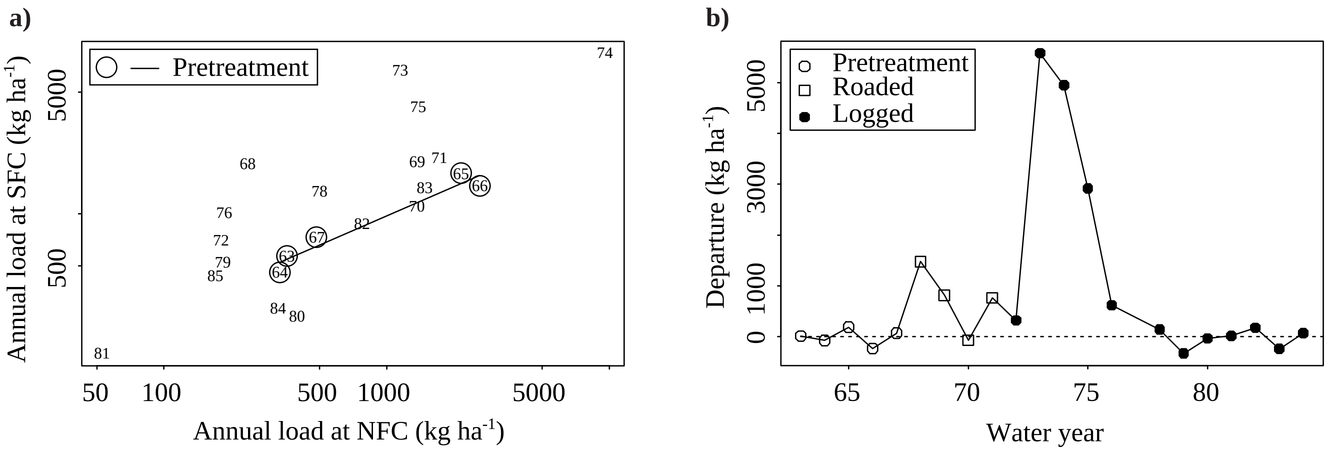

Figure 2—(a) Relation between estimated annual suspended sediment loads at South Fork Caspar Creek (SFC) and North Fork Caspar Creek (NFC) from 1963 to 1985. Pretreatment regression line is fit to the water years before roading and logging activity in the South Fork. (b) Time series of departures from the regression line.

data, so it is still suspect. If the adjustment of Rice and others (1979) is applied in my analysis, the revised increase in suspended sediment load is 2,835 kg ha^{-1}yr^{-1}, or an increase of 331 percent over that predicted for the 6-yr period. The adjusted figure reported for the 5-yr period (1972-1976) by Rice and others was 3,245 kg ha^{-1}yr^{-1}, an increase of 354 percent over that predicted.

Although no statistically significant logging effect on pond accumulation was detected, regression analysis using total sediment load (including data from 1974) revealed a similar pattern of impacts as that of the suspended load. The increased total sediment load after logging of the South Fork amounted to 2,763 kg ha^{-1}yr^{-1}, or an increase of 184 percent over that predicted for the 6-yr period by the regression.

Annual Sediment Loads after Logging the North Fork

The calibration period used in the North Fork analysis includes 1979-1985, the years after the South Fork's apparent recovery, as well as 1963-1967. The years 1986-1989 were not included in the calibration period because the Y and Z units were logged in 1985 and 1986. Applying the Chow test, neither 1986-1989 ($p = 0.43$) nor 1990-1995 ($p = 0.53$) was found to differ significantly from the suspended sediment calibration regression (*fig. 3a*). The (nonsignificant) departures from the regression predictions averaged 118 kg ha^{-1}yr^{-1}, amounting to just 28 percent above that predicted for the 6-yr period by the regression (*fig. 3b*). No effect was detected for pond accumulation by itself or total sediment load. For total sediment load, the (nonsignificant) departures from the regression predictions averaged -80 kg ha^{-1}yr^{-1}, or 8 percent below that predicted for the 6-yr period by the regression.

The absolute numbers reported in the above and earlier analyses of the South Fork logging (Rice and others 1979) must be viewed with reservation. The suspended load estimates were based on hand-drawn sediment rating curves describing the relation between the concentration of samples collected in a given year to the discharge levels at which they were collected. In several years, samples were not available from all discharge classes, so it was necessary to extrapolate the relation between concentration and discharge to higher or lower unrepresented classes. Also, a majority of the samples from the years 1963-1975 were collected using single-stage samplers that are filled only during the rising limb of hydrographs. In most storm events we have measured at Caspar Creek, the concentrations are markedly higher on the rising limb of the hydrograph than for equivalent discharges on the falling limb (e.g., *fig. 4*). Therefore, the fitted concentrations were likely too high. A plot of estimated sediment loads at NFC against annual water yield for the pre-logging years (*fig. 5*) suggests that there may be a positive bias during the single-stage years. The error associated with this method certainly varies from year to year, depending on the numbers of single-stage and manual samples and their distribution relative to the hydrographs. However, the plot indicates that loads were overestimated by a factor of between 2 and 3 in the range where most of the data occur. A comparison of the annual loads for the years 1986-1995 with annual sums of storm loads (the most accurate) shows very little bias, indicating that bias in the early years resulted mainly from sampling protocols rather than the computational method, which was the same for all years in this analysis.

North Fork Analysis Using Unlogged Subwatersheds as Controls

Because of improved and more intensive sampling methods, the suspended sediment loads for storm events beginning in 1986 are known far more accurately than the annual loads used in the NFC/SFC contrasts presented above. Four unlogged control watersheds were available (HEN, IVE, MUN, and SFC) for the analysis of storm loads. Unfortunately, only one large storm was available before logging. That storm was missed at SFC because of pumping sampler problems. Because of various technical difficulties, not all storms

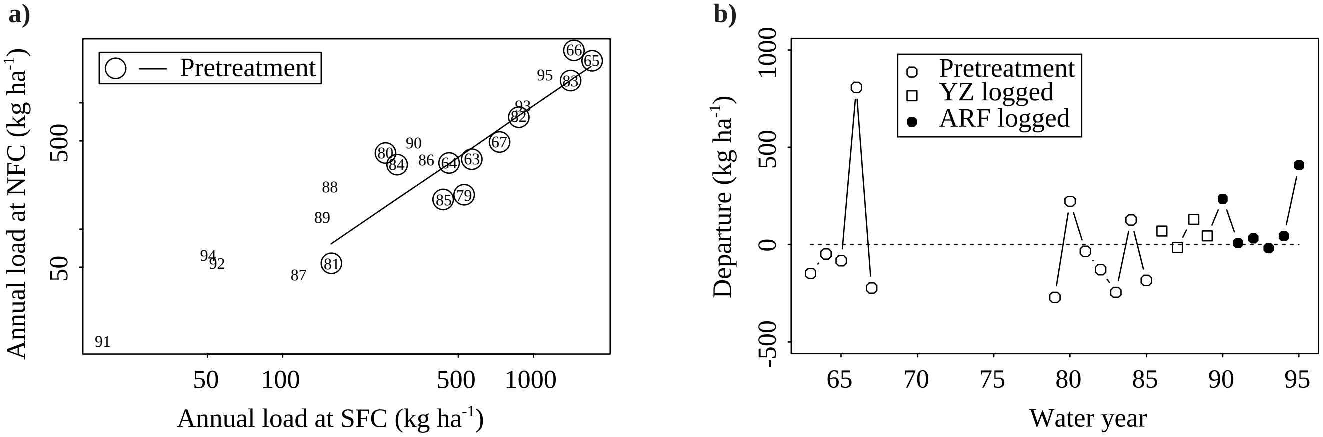

Figure 3—(a) Relation between estimated annual suspended sediment loads at North Fork Caspar Creek (NFC) and South Fork Caspar Creek (SFC) from 1963 to 1967 and 1979 to 1995, excluding years when sediment was elevated following logging in the South Fork. Pretreatment regression line is fit to the water years before roading and logging activity in the North Fork. (b) Time series of departures from the regression line.

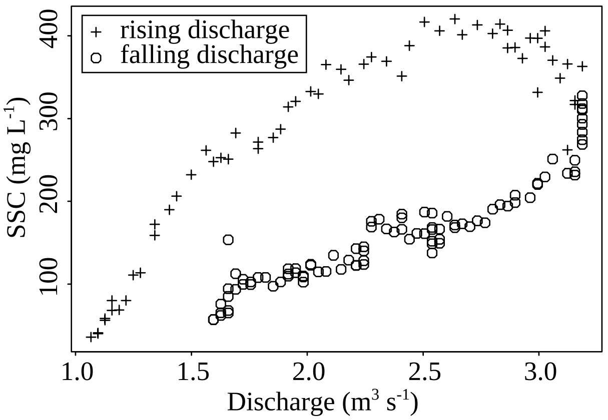

Figure 4—Storm event at lower main-stem station ARF, January 13-14, 1995, with water discharge and laboratory sediment concentrations (SSC) at 10-minute intervals.

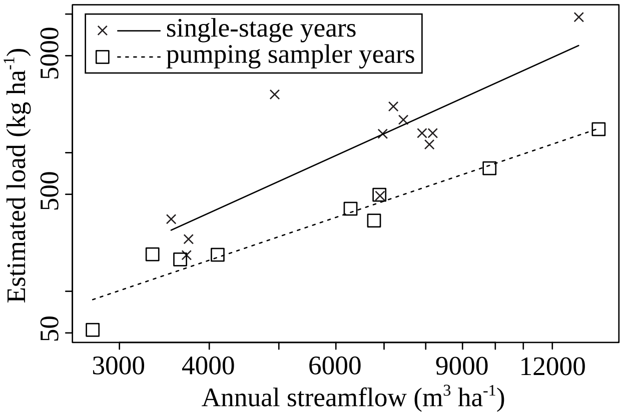

Figure 5—Relations between estimated annual suspended sediment loads and annual streamflow at North Fork Caspar Creek (NFC) prior to logging. Illustrates that load estimates based on sediment rating curves depend systematically on sampling protocols.

were adequately sampled at each station. However, the sample size for analyses was increased by using the mean of available data from the three tributary control watersheds, HEN, IVE, and MUN, in each storm. (SFC was eliminated because it had lower pretreatment correlations with the North Fork stations.) This mean (denoted HIM) provided a pretreatment sample size of 17 storms. The more accurate sediment loads, better controls, and larger sample size gave this analysis greater reliability and increased power to detect changes than the annual load analysis.

A weakness in analyses of logging effects at NFC was the need to use 1986-1989 as a calibration period even though 12 percent of the area had been clearcut. The clearcut area might be expected to somewhat diminish the size of the effect detected. The occurrence of only one large storm event before logging is mitigated by the fact that it was thoroughly sampled at both NFC and the three controls.

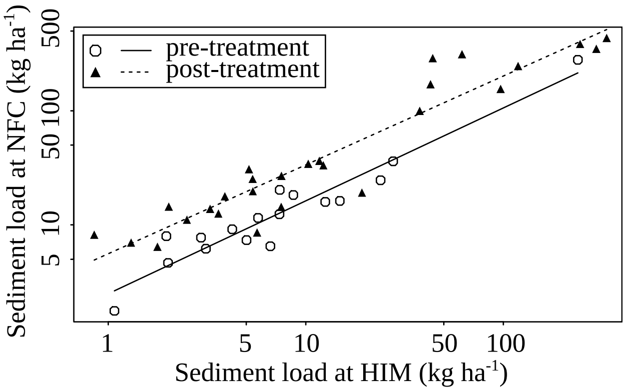

Figure 6—Relation between storm suspended sediment loads at North Fork Caspar Creek (NFC) and HIM control (mean suspended load of unlogged tributaries HEN, IVE, and MUN) from 1986 to 1995. Pretreatment regression line is based on storms in water years 1986-1989, before the major logging activity began.

An average of 59 sample bottles were collected at each of the four stations, and all the standard errors were less than 10 percent of the estimated loads, so there is little doubt about this point's validity.

Figure 6 shows regression lines fit to the suspended storm loads at NFC versus those at HIM before and after logging began in the spring of 1989. There was clearly an increase in suspended loads in small storms after logging began. In large storms there also seems to be an effect, although some post-treatment points are very close to the one large pretreatment point. The Chow test for a change after logging was significant with $p = 0.006$. The increases over predicted load, summed over all storms in the post-treatment period, average 188 kg $ha^{-1}yr^{-1}$, and amount to an 89 percent increase over background. The storms in this analysis represent 41 percent of the 1990-1996 streamflow at NFC, but carried approximately 90 percent of the suspended sediment that passed over the weir (based on figure 2 of Rice and others 1979).

A 3,600-m^3 landslide that occurred in the Z cut unit (Preface, fig. 2, these proceedings) increased sediment loads at the NFC gaging station starting in January 1995. NFC was the only gage downstream from this slide. The sum of suspended loads from storms preceding the landslide was 47 percent higher (64 kg $ha^{-1}yr^{-1}$) than predicted. The sum of suspended loads from storms after the landslide was 164 percent higher (150 kg $ha^{-1}yr^{-1}$) than predicted.

Individual Regressions for Subwatersheds

Similar analyses for each of the subwatersheds in the North Fork (*fig. 7* and *table 1*) indicate increased suspended sediment loads in all the clearcut tributaries except KJE. Sediment loads in the KJE watershed appear to have decreased after logging. The only partly clearcut watershed on a tributary (DOL) also showed highly significant increases in sediment loads. The upper main-stem stations (JOH and LAN) showed no effect after logging, and the lower main-stem stations (FLY and ARF) experienced increases only in smaller storms. Summing suspended sediment over *all* storms, the four main-stem stations all showed little or no change (*table 1*).

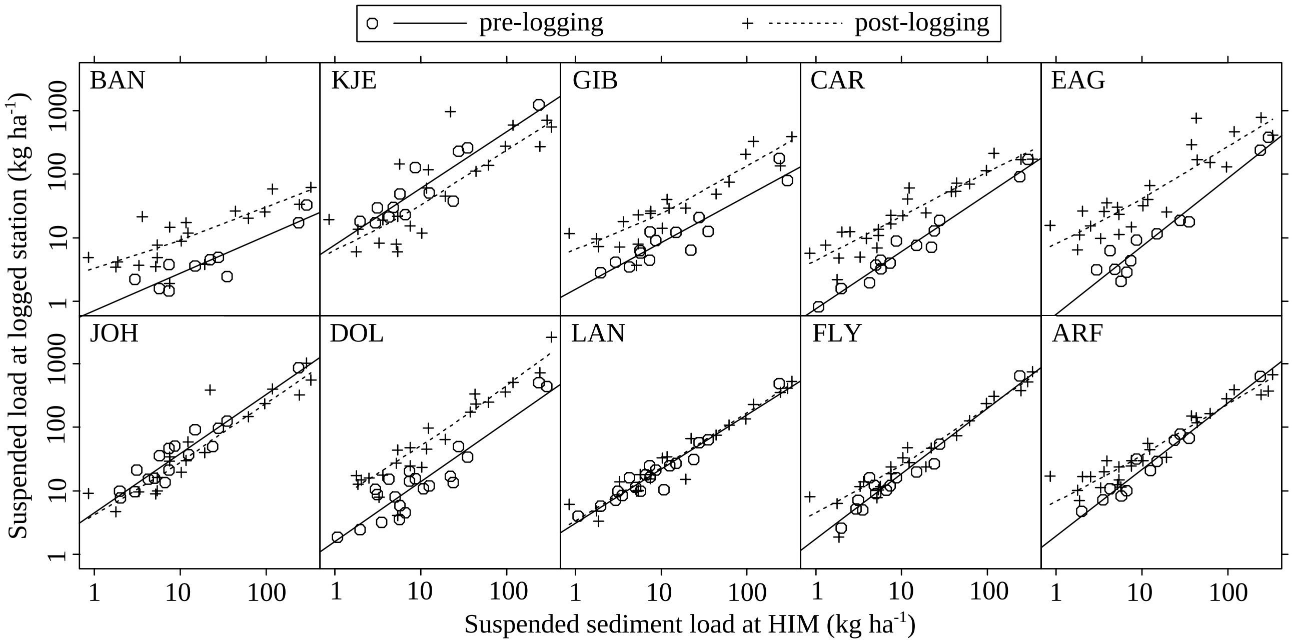

Figure 7—Relations between storm suspended sediment loads at logged subwatersheds in the North Fork and HIM control (mean suspended load of unlogged tributaries HEN, IVE, and MUN) from 1986 to 1995. Pre-logging regression lines are based on pretreatment years that are specific to each subwatershed. Post-logging relations are not assumed to be linear, hence were fitted by locally weighted regression (Cleveland 1993).

***Table 1**—Summary of changes in suspended sediment load (summed over storms) after logging in North Fork subwatersheds. Predicted loads are computed from pre-treatment linear regressions between the logarithms of the storm sediment load in the treated watershed and the mean of the storm sediment loads at the control watersheds HEN, IVE, and MUN. Predictions were corrected for bias when back-transforming from logarithmic units. The number of years in the post-logging period varies from 4 to 6, depending upon when the watershed was logged and whether or not monitoring was discontinued in water year 1996.*

Treated watershed	Number of years	Observed (kg ha^{-1} yr^{-1})	Predicted (kg ha^{-1} yr^{-1})	Change (kg ha^{-1} yr^{-1})	Change (%)
ARF	4	505	591	-86	-15
BAN	4	85	28	57	203
CAR	5	240	108	132	123
DOL	5	1130	306	824	269
EAG	5	710	210	500	238
FLY	5	536	555	-19	-3
GIB	4	358	119	239	200
JOH	5	667	865	-198	-23
KJE	5	821	1371	-551	-40
LAN	5	420	400	20	5
NFC	6	465	246	219	89

Aggregated Regression Model for Subwatersheds

To evaluate the relationships between suspended sediment load increases and possible explanatory variables, an aggregated regression model was fit simultaneously to all the subwatershed storms. The model utilized 367 estimated loads from 51 storms when HIM was used as the control or 333 estimated loads from 43 storms when HI (the mean of HEN and IVE) was used. Two regression coefficients were fitted for each watershed. A number of disturbance measures were considered (*table 2*), as well as an area term designed to describe cumulative effects, and a term explaining sediment increases in terms of flow increases. A great deal of effort went into developing a model that would permit valid tests of hypotheses concerning cumulative watershed effects. Therefore, the response model is coupled with a covariance model that describes variability in terms of watershed area and correlation among subwatershed responses as a function of distance between watersheds. These models were solved using the method of maximum likelihood and will be described in detail in a separate publication (Lewis and others 1998).

Departures from sediment loads predicted by the aggregated model for undisturbed watersheds were modest. The median increase in storm sediment load was 107 percent in clearcuts and 64 percent in partly clearcut watersheds. The median annual increase was 109 percent (58 kg ha^{-1}yr^{-1}) from clearcut watersheds and 73 percent (46 kg ha^{-1}yr^{-1}) from partly clearcut watersheds. The absolute flux values are underestimated somewhat because they include only sediment measured in storms, and no effort has been made to adjust for missing data. However, the major storms have been included, and virtually all of the sediment is transported during storms. Uncertainty due to year-to-year variability is certainly a much greater source of error.

The most important explanatory variable identified by the model was increased volume of streamflow during storms. Storm flow predictions (Ziemer, these proceedings) were based on an aggregated model analogous to that used for predicting sediment loads. The ratio of storm sediment produced to that predicted for an unlogged condition was positively correlated to the ratio of storm flow produced to that predicted for an unlogged condition (*fig. 8*). This result is not unexpected because, after logging, increased storm flows in the treated watersheds provide additional energy to deliver and transport available sediment and perhaps to generate additional sediment through channel and bank erosion.

Table 2*—Explanatory variables considered in modeling storm sediment loads in North Fork subwatersheds.*

- Mean unit area suspended load from control watersheds
- Excess storm flow volume relative to that of control watersheds
- Time since logging completed
- Timber removed per unit watershed area
- Areas of various disturbances as proportion of watershed:
    - Cable, tractor yarding
    - Stream protection zones, thinned areas
    - Burning (low intensity, high intensity)
    - Road cuts, fills, running surfaces
    - Skid trail cuts, fills, operating surfaces
    - Landing cuts, fills, operating surfaces
- Areas of above disturbances within 46 m (150 ft) of a stream channel
- Length of impacted stream in above disturbances per unit watershed area
- Length of cabled corridors per unit watershed area
- Watershed area

Whereas individual watersheds show trends indicating increasing or decreasing sediment loads, there is no overall pattern of recovery apparent in a trend analysis of the residuals from the model (*fig. 9a*). This is in contrast with the parallel model for storm flow volume (*fig. 9b*), and suggests that some of the sediment increases are unrelated to flow increases.

Other variables found to be significant were road cut and fill area, and, in models using the HI control, the length of unbuffered stream channel, particularly in burned areas. Under California Forest Practice Rules in effect during the North Fork logging, buffers were not required for stream channels that do not include aquatic life and are not used by fish within 1,000 feet downstream except in confluent waters. As discussed earlier, one must be cautious about drawing conclusions about cause and effect when treatments are not randomly assigned to experimental units and replication is limited. Increases in sediment load in one or two watersheds can create associations with any variable that happens to have higher values in those watersheds, whether or not those variables are physically related to the increases. In this study, the contrast in response is primarily between watershed KJE, where sediment loads decreased, versus watersheds BAN, CAR, DOL, EAG, and GIB. Watershed KJE was unburned and also had the smallest amount of unbuffered stream of all the cut units. Watersheds EAG and GIB were burned and had the greatest amount of unbuffered stream in burned areas. Watershed EAG experienced the largest sediment increases and also had the greatest proportion of road cut and fill area. Because EAG was not unusually high in road surface area, the large road cut and fill area indicates that the roads in EAG are on steeper hillslopes.

There is little field evidence of sediment delivery from roads in

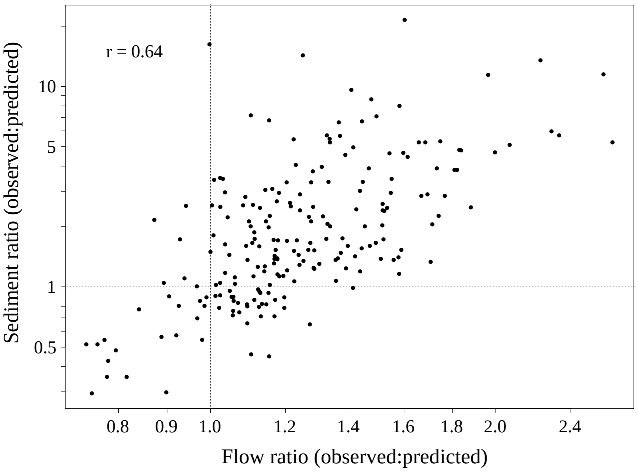

Figure 8—Relation between post-logging ratios of observed to predicted storm flow and suspended sediment load for all North Fork subwatersheds. Predictions are for undisturbed watersheds based on aggregated regression models using HI control (mean response of unlogged tributaries HEN and IVE).

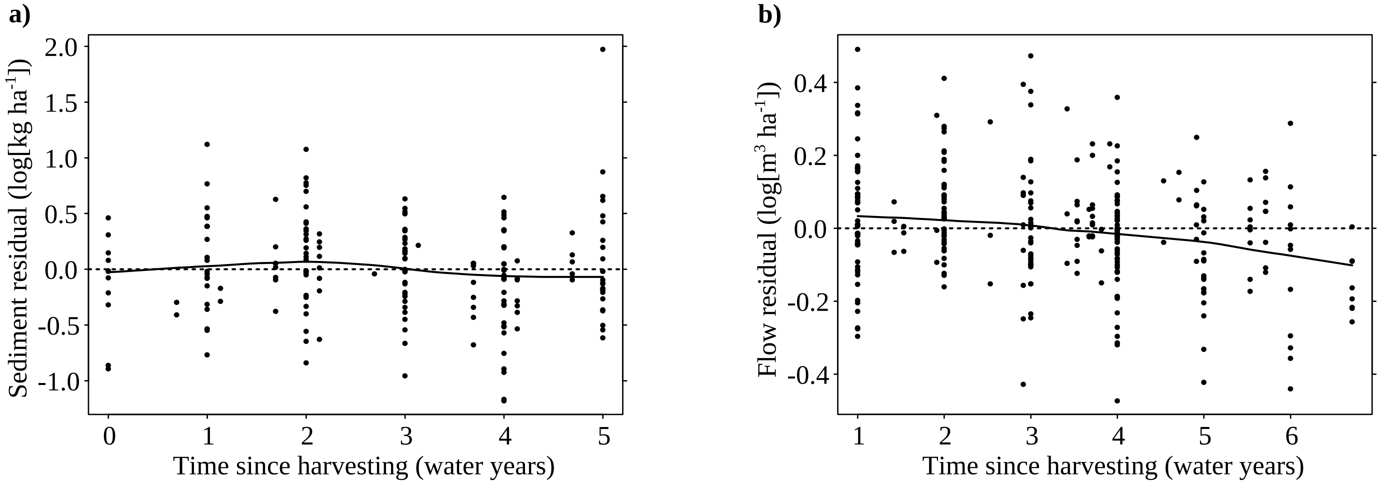

Figure 9—Relation between post-logging residuals from aggregated models and time (difference in water years) since harvesting. (a) model for storm suspended sediment loads, and (b) model for storm flow volumes. Curves were fitted by locally weighted regression (Cleveland 1993).

the North Fork watershed. In the inventory of failures greater than 7.6 m^3, only 8 of 96 failures, and 1,686 of 7,343 m^3 of erosion were related to roads. Nearly all of this road-related erosion was recorded as remaining on-site, and none of the road-related failures occurred in the EAG watershed. Based on the 129 random erosion plots (Rice 1996), the road erosion in EAG was 9.3 m^{3}ha^{-1}, compared to 34.5 m^{3}ha^{-1} for KJE and 16.6 m^{3}ha^{-1} for all roads in the North Fork. Thus it seems that the appearance of road cuts and fills in the model resulted from a spurious correlation.

On the other hand, channel reaches subjected to intense broadcast burns did show increased erosion from the loss of woody debris that stores sediment and enhances channel roughness (Keppeler, electronic communication). And increased flows, accompanied by soil disruption and burning in headwater swales, may have accelerated channel headward expansion, and soil pipe enlargements and collapses observed in watershed KJE (Ziemer 1992) and in EAG, DOL, and LAN.

Based on the 175 random erosion plots in harvest areas (Rice 1996), the average hillslope erosion rates in the burned watersheds EAG and GIB were 153 m^{3}ha^{-1} and 77 m^{3}ha^{-1}, respectively, the highest of all the watersheds. The average rate for the unburned clearcut watersheds BAN, CAR, and KJE was 37 m^{3}ha^{-1}. These figures include estimates of sheet erosion, which is difficult to measure and may be biased towards burned areas because it was easier to see the ground where the slash had been burned (Keppeler, verbal communication). About 72 percent of EAG and 82 percent of GIB were judged to be thoroughly or intensely burned, and the remainder was burned lightly or incompletely. It is unknown how much of this hillslope erosion was delivered to stream channels, but the proportion of watershed burned was not a useful explanatory variable for suspended sediment transport.

The failure inventory identified windthrow as another fairly important source of sediment. Of failures greater than 7.6 m^3, 68 percent were from windthrow. While these amounted to only 18 percent of the failure volume measured, 91 percent of them were within 15 m of a stream, and 49 percent were in or adjacent to a stream channel. Because of the proximity of windthrows to streams, sediment delivery from windthrow is expected to be disproportionate to the erosion volume. Windthrows are also important as contributors of woody debris to channels (Reid and Hilton, these proceedings), and play a key role in pool formation (Lisle and Napolitano, these proceedings). Because woody debris traps sediment in transport, it is unknown whether the net effect of windthrow on sediment transport was positive or negative.

Cumulative Effects

A full explanation of the rationale and methods of testing for cumulative watershed effects is beyond the scope of this paper, and final results on this topic will be reported by Lewis and others (1998). Preliminary results will simply be stated here.

I have considered three types of information that the aggregated model provides about the cumulative effects of logging activity on suspended sediment loads:

1. Were the effects of multiple disturbances additive in a given watershed?
2. Were downstream changes greater than would be expected from the proportion of area disturbed?
3. Were sediment loads in the lower watershed elevated to higher levels than in the tributaries?

The response being considered in all of these questions is the suspended sediment load per unit watershed area for a given storm event. Watershed area was used in the model to represent distance downstream.

The first question may be answered partly by looking at the forms of the storm flow and sediment models. Analyses of the residuals and covariance structures provide good evidence that the models are appropriate for the data, including the use of a logarithmic response variable. This implies a multiplicative effect for predictors that enter linearly and a power function for predictors that enter as logarithms. It turns out that the flow response to logged area is multiplicative, and the sediment response to flow increases is a power function. These effects, however, are *approximately* additive within the range of data observed for watersheds receiving flow from multiple cut units.

The second question was addressed by testing terms formed from the product of disturbance and watershed area. If the coefficient of this term were positive, it would imply that the effect of a given disturbance proportion increases with watershed size. A number of disturbance measures were considered, including road cut and fill area and length of unbuffered stream channels. None of the product terms were found to have coefficients significantly greater than zero, indicating that suspended load increases were not disproportionately large in larger watersheds. To the contrary, the sum of the observed sediment loads at the four main-stem stations were all within 25 percent of the sum of the loads predicted for undisturbed watersheds (*table 1*). Apparently, much of the sediment measured in the tributaries has been trapped behind woody debris or otherwise stored in the channels, so that much of it has not yet been measured downstream.

There is, however, one subwatershed where this second type of cumulative effect may be occurring. Watershed DOL, only 36 percent cut, includes the 100 percent cut watershed EAG, yet the sediment increases (269 percent at DOL versus 238 percent at EAG) have been similar. The increases in DOL seem to be related to channel conditions created in the historic logging (1900-1904) and, possibly, to increased flows from recent logging. At the turn of the century, the channel between the DOL and EAG gaging stations was used as a "corduroy road" for skidding logs by oxen. Greased logs were half-buried in the ground at intervals equal to the step length of the oxen (Napolitano 1996), and an abundance of sediment is stored behind them today (Keppeler, electronic communication). Energy available during high flows may be mobilizing sediment stored behind these logs. In the lower reach, the channel has a low width:depth ratio and is unable to dissipate energy by overflowing its banks. The high banks in this reach would be particularly vulnerable to increased peak flows, and have failed in a number of places in the years since EAG was logged.

The third question was addressed by testing watershed area as a linear term in the model. The coefficient of watershed area was positive ($p = 0.0023$), implying that the response, suspended sediment transport per unit watershed area, tends to increase downstream in the absence of disturbance. This tendency (with the exception of watershed KJE) is apparent in the pretreatment lines fit by least squares (*fig. 10a*), and could be reflecting the greater availability of fine sediment stored in these lower gradient channels. The relevance to cumulative effects is that downstream locations might reach water quality levels of concern with a smaller proportion of watershed disturbance than upstream locations.

To the extent that larger watersheds reflect average disturbance rates and therefore have smaller proportions of disturbance than the smallest disturbed watersheds upstream, one might expect sediment loads downstream to increase by less than those in the logged tributaries, reducing the overall variability among watersheds. In addition, as mentioned before, some of the sediment may be stored for several years before reaching the lower stations. That is what we observed in this study—the post-treatment regression lines (*fig. 10b*) were much more similar among watersheds than the pretreatment lines, and the main-stem stations no longer transported the highest sediment loads relative to watershed area.

Discussion

North Fork versus South Fork

My analysis of the South Fork logging data used a different model than was used by Rice and others (1979). However, the estimated increases in sediment loads were similar. For example, they reported suspended load increases of 1,403 kg $ha^{-1}yr^{-1}$ in the year after road construction and 3,254 kg $ha^{-1}yr^{-1}$ for the 5-yr period after logging. For the same periods, I estimated increases of 1,475 and 2,877 kg $ha^{-1}yr^{-1}$. Reversing the roles of the two watersheds for the later North Fork logging, the same analysis was unable to detect an effect. However, analysis of storm event loads from 1986 to 1996, using smaller subwatersheds within the North Fork as controls that had similar 19th-century logging histories as the whole North Fork, indicated that storm loads at NFC had increased by 188 kg $ha^{-1}yr^{-1}$. When comparing these figures, one should consider the differences between the water years 1972-1978 and 1990-1996, as well as differences in sampling methodologies that could have biased the estimated sediment loads. The mean annual unit area streamflow in the control (NFC) was 63 percent higher in 1972-1978 than that in the control (SFC) in 1990-1996. There is a surprisingly good relation between annual excess sediment load (departures from the pre-treatment regression) and water discharge in each of the studies (*fig. 11*). For equivalent flows, excess sediment loads in the South Fork analysis were six to seven times those in the North Fork analysis. It is probable that the sampling methods in the 1960's and 1970's resulted in overestimation of sediment loads in the South Fork analysis by a factor of 2 or 3. Therefore, comparisons between *relative* increases are more appropriate. Excess suspended load was 212 percent to 331 percent (depending on whether an adjustment is made for the 1974 North Fork landslide) after logging the South Fork, and 89 percent after logging the North Fork, suggesting that the effect of logging on suspended sediment load was 2.4 to 3.7 times greater in the South Fork than in the North Fork. These estimates approximately agree with estimates (Rice 1996) that both erosion and the sediment delivery ratio in the South Fork were about twice that in the North Fork.

Subwatersheds and KJE Anomaly

Analyses of the 10 treated subwatersheds in the North Fork drainage show suspended load increases at the gaging stations located

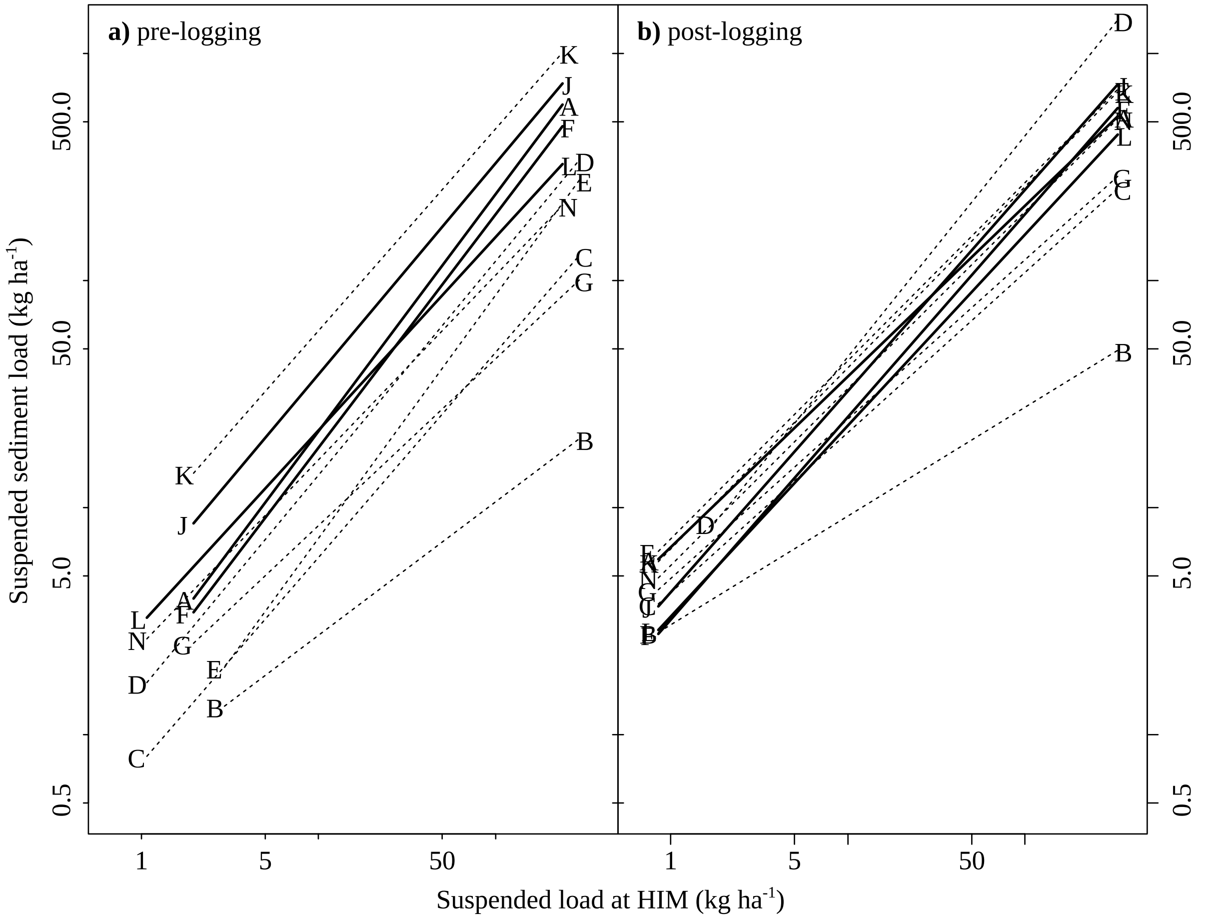

Figure 10—Regression lines for storm suspended sediment loads at treated watersheds in the North Fork, predicted from HIM control (mean suspended load of unlogged tributaries HEN, IVE, and MUN). (a) pre-logging, and (b) post-logging. Solid lines represent main-stem stations and dashed lines represent tributary stations.

immediately below clearcut units with one exception. At KJE, loads have decreased. A possible explanation for this anomaly lies in the tributary channel morphology. The stream channel in the KJE watershed is an extension of the main stem of the North Fork. It is (and, before recent logging, was) more deeply incised than the other tributaries, and it has the lowest gradient of tributaries other than the reach between the DOL and EAG gaging stations. The channel may have taken its gully-like form after the historic logging that took place between 1860 and 1904, when streams and streambeds were used as conduits for moving logs (Napolitano 1996). In any case, KJE had the highest pre-logging (1986-1989) unit area sediment loads of any of the tributaries (*fig. 10a*). Sediment in its channel is plentiful and the banks are actively eroding. It is likely, then, that the pre-logging sediment regime in KJE may have been energy-limited, which is more characteristic of disturbed watersheds. That is, sediment discharge was determined more by the ability of the stream to transport sediment than by the availability of sediment to be transported.

After logging, woody debris was added to the channel, and the number of organic steps in the buffered stream above KJE nearly doubled. Farther upstream, the channel was no longer shaded by the forest canopy and became choked with new redwood sprouts, horsetails, berry vines, and ferns, as well as slash that was introduced during logging. Although small storm flows did increase after logging, it is possible that channel roughness could have increased enough to reduce the energy available for sediment transport. An energy-limited stream would respond to increased sediment supply and reduced energy by reducing sediment transport. On the other hand, tributaries in a supply-limited sediment regime would have responded to a combination of increased sediment supply and reduced energy by increasing sediment transport. At some point, the increased supply probably converted these channels to an energy-limited regime, at which point stream power became the primary factor controlling variation in the increased transport levels. Rice and others (1979) concluded that is what happened after logging in the South Fork.

The aggregated regression for storm flow volumes (Lewis and others 1998; Ziemer, these proceedings) showed that flow increases

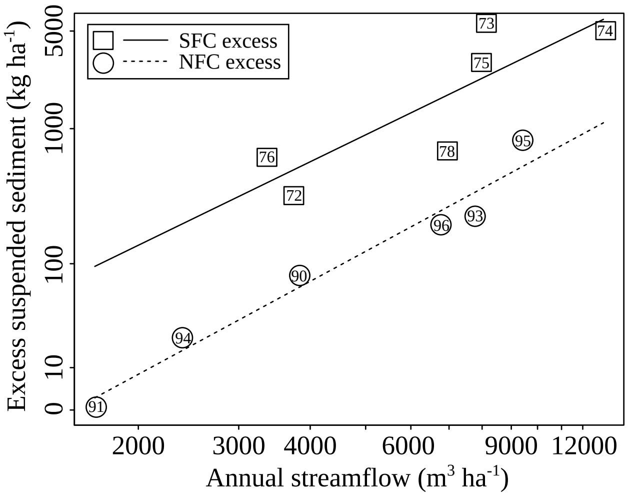

Figure 11—Relations between annual excess suspended sediment and annual streamflow for six years after logging in the South Fork and North Fork. South Fork excess loads are the departures from the pretreatment regression of figure 2. North Fork excess loads are the sums of storm departures from the pretreatment regression of figure 6.

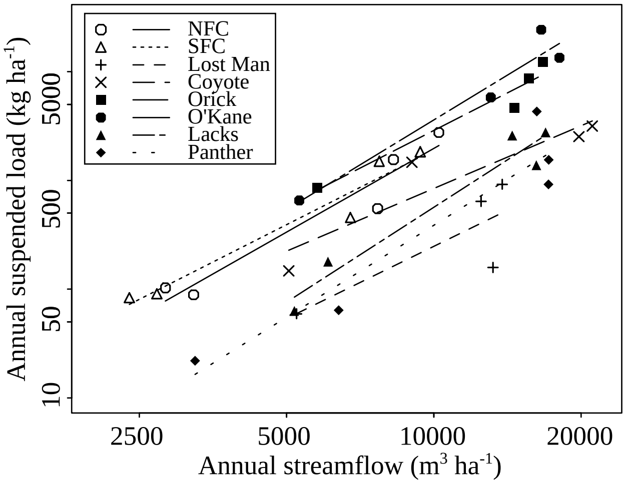

Figure 12—Relation between annual suspended sediment loads and annual streamflow for water years 1992-1996 at North Fork Caspar Creek (NFC), South Fork Caspar Creek (SFC), and 6 gaging stations in the vicinity of Redwood National Park. Caspar Creek sediment loads were divided by 0.6 to account for suspended sediment settling in the weir ponds.

could be largely explained by the proportion of a watershed logged, an antecedent wetness index, and time since logging. The aggregated regression for storm suspended sediment showed that much of the variability in suspended sediment load could, in turn, be explained by the flow increases. The implication is that, after logging, the channels were indeed in an energy-limited regime.

Flow increases accounted for only part of the variability in sediment production. Road systems would typically be expected to account for much of the sediment. However, in this case, roads were relatively unimportant as a sediment source because of their generally stable locations on upper hillslopes far from the stream channels. Field observations of increased bank erosion and gully expansion in clearcut headwater areas indicate that some of the suspended sediment increases were associated with the length of unbuffered stream channels in burned areas and, to a lesser degree, in unburned areas. Further indirect evidence that factors besides flow volume are elevating the suspended loads is that storm flows show a recovery trend, whereas storm suspended loads do not (*fig. 9*). This supports the hypothesis that the sediment regime has changed to one that will support elevated transport levels until the overall sediment supply is depleted. This can happen only after erosion and delivery rates to the channel decline and flows have been adequate to export excess sediment stored in the channels.

Cumulative Effects

Before logging, the larger main stem watersheds generally yielded the highest unit area sediment loads. But the increases after logging were greatest in the tributaries, resulting in a much narrower range of transport, for a given storm size, after logging (*fig. 10*). The North Fork of Caspar Creek is a small watershed (4.73 km^2). To see whether these results might be generalizable to larger watersheds, annual sediment loads for water years 1992-1996 were plotted against annual water yield (*fig. 12*) for NFC, SFC, and six gaging stations on streams in the vicinity of Redwood National Park (RNP). These watersheds were selected because of the high quality of their data and because, like Caspar Creek, they are underlain by the highly erodible Franciscan formation and historically supported mostly redwood forest with varying amounts of Douglas-fir. Caspar Creek receives less rainfall than the RNP watersheds, hence the lower annual flows.

In contrast to Caspar Creek, the RNP main-stem stations (Redwood Creek at Orick, 720 km^2, and at O'Kane, 175 km^2) continue to yield higher sediment loads than the RNP tributaries even after intensive management. Except for Little Lost Man Creek, these watersheds have been heavily logged at various times over the past 50 years, including the 1980's and 1990's. (Ground disturbance from logging in these watersheds was much more severe than that in Caspar Creek.)

The watershed with the lowest sediment loads is the unlogged Little Lost Man Creek (9.0 km^2), which is also the smallest of the RNP watersheds. Lacks Creek (44 km^2), Coyote Creek (20 km^2), and Panther Creek (16 km^2) are high-gradient (4-7 percent) channels in three different geologic subunits of the Franciscan formation (Harden and others 1982). Part of the explanation for the higher sediment loads at the main-stem stations may lie in the greater abundance of fine sediments available for transport in these low gradient (<1 percent) channels. Note that the Caspar Creek main stems are intermediate in both stream gradient (~1 percent) and sediment transport between the RNP tributaries and main stems. Regardless of the cause, if these lower reaches have the poorest water quality, then the incremental effect of an upstream disturbance may be cause for concern whether or not a water quality problem develops at the site of the disturbance. In other words, activities that have acceptable local consequences on water quality might have unacceptable consequences farther downstream when the preexisting water quality downstream is closer to harmful levels.

Cumulative effects considered in this paper were limited to a few hypotheses about water quality that could be statistically evaluated. But cumulative effects can occur in many ways. For example, resources at risk are often quite different in downstream areas, so an activity that has acceptable local impacts might have unacceptable offsite impacts if critical or sensitive habitat is found downstream. For a much broader treatment of cumulative effects see the discussion by Reid (these proceedings).

Conclusions

The main conclusions from these analyses are:

- Improved forest practices resulted in smaller increases in suspended load after logging the North Fork than after logging the South Fork. Increases were 2.4 to 3.7 times greater in the South Fork with roads located near the stream, all yarding by tractor, and streams not protected.
- Much of the increased sediment load in North Fork tributaries was related to increased storm flow volumes. With flow volumes recovering as the forest grows back, these increases are expected to be short-lived.
- Further sediment reductions in the North Fork probably could have been achieved by reducing or preventing disturbance to small drainage channels.
- Sediment loads are probably affected as much by channel conditions as by sediment delivery from hillslopes. The observed changes in sediment loads are consistent with conversion of those channels that were supply-limited before logging to an energy-limited regime after logging.
- The effects of multiple disturbances in a watershed were approximately additive.
- With one exception, downstream suspended load increases were no greater than would be expected from the proportion of area disturbed. To the contrary, most of the increased sediment produced in the tributaries was apparently stored in the main stem and has not yet been measured at the main-stem stations.
- Before logging, sediment loads on the main stem were higher than on most tributaries. This was no longer the case after logging. However, limited observations from larger watersheds suggest that downstream reaches in some watersheds are likely to approach water-quality levels of concern before upstream reaches.

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