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Erosion associated with cable and tractor logging in north-western California

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Abstract. Erosion and site conditions were measured at 102 logged plots in northwestern California. Erosion averaged 26.8 m^3/ha. A log-normal distribution was a better fit to the data. The antilog of the mean of the logarithms of erosion was 3.2 m^3 /ha. The Coast District Erosion Hazard Rating was a poor predictor of erosion related to logging. In a new equation that "explained" about 40 percent of the variability in erosion, yarding method was associated with a 3.7-fold difference in erosion, aspect with a 4.3-fold difference, geologic type with a 13.5-fold difference, and slope with a 16-fold difference. The analysis suggests that an additional source of variation was operative that may be related to how the logging was done. Future investigations, therefore, should focus more on the conduct of logging operations than descriptions of the site logged.

Erosion associée à l'exploitation forestière au tracteur et au débardage par câble dans la Californie du Nord-ouest.

Résumé. L'érosion et les conditions de site ont été mesurées à 102 parcelles exploitées dans la Californie du Nord-ouest. L'érosion était en moyenne 26.8 m^3/ha. Cependant, une distribution logarithmique

normale convient mieux aux données. L'antilogarithme de la moyenne de cette distribution était 3.2 m^3/ha. L'evaluation des Hasards de l'Erosion par le District Côtier a mal prédit 1'erosion associée à 1'exploitation forestiére. Une nouvelle équation fondée sur la pente, 1'exposition, la géologie, la méthode de débusquage "a expliqué" environ 40 pour-cent de la varabilité de l'érosion. Elle a indiqué que la méthode de débusquage était associée à une différence de 3.7 fois; l'exposition, à une differénce de 4.3 fois; le type géologique, a une différence de 13.5 fois; et la pente étatit rattachée a une différence de 16 fois, quant à l'érosion. L'analyse a suggéré une source additionnelle de variation, probablement ayant rapport à la méthode d'exploitation. Par conséquent, les investigations futures devraient concentrer plus d'attention sur la méthode de l'exploitation forestiére et ne pas se borner à décrire le site où elle a lieu.

INTRODUCTION

Deciding to harvest timber from a tract of land implies the acceptance of tradeoffs. In much of the Pacific Rim Steeplands, one tradeoff is the decline of water quality and fish habitat balanced against the value of forest products acquired by logging. In response to growing public concern in the western United States, forest practice laws have been enacted to ensure that the benefits and losses resulting from logging are properly balanced.

In 1973, the California Legislature enacted a major revision of the State's Forest Practices Act. Each forest district is required to issue rules governing logging

practices. The rules usually modify some practices based on estimates of the risk of erosion. For the Coast Forest District, innorthwestern California, a team of foresters and soil scientists developed an Erosion Hazard Rating (EHR) by extrapolating from regression equations of H.W. Anderson (1972, 1974). The EHR system, in its original form, is based on slope, geology, soil depth, soil texture, and mean annual rainfall. Three variations are available, including the most commonly used form, which is based on slope, soil series, andmean annual precipitation. From the start, however, the value of the EHR has been questioned. The regression equations (Anderson, 1972, 1974) related sedimentation to drainage basin conditions rather than erosion to site conditions. Furthermore, the EHR is a relative rating - it is not explicitly tied to erosion.

This paper reports a study of how well erosion associated with logging in the Coast Forest District of northwestern California is correlated with the Erosion Hazard Rating, and develops a more effective rating system.

METHODS

A stratified sampling scheme was used to obtain maximum utility from the data we collected. The strata included four slope classes, five annual rainfall classes, five geologic types (later expanded to six), three lengths of time-since-logging, and two yarding methods. When sampling from these strata, we attempted to get a uniform distribution of plots

among the 600 cells in the complete data matrix. This stratification yielded a well distributed sampling of conditions and minimised the correlations which naturally occur among some variables. The highest individual correlation, between slope and yarding method, was 0.51. The multiple correlations between yarding method and the geologic types and mean annual precipitation and the geologic types were 0.68.

The plots were rectangular, about 201 m wide, and extended up or down a slope to include all area yarded to a particular landing. Logs were skidded downhill on almost all the tractor-yarded plots. All cable-yarded plots were yarded uphill. About 100 variables were measured on each plot to describe the site, its spatial variability, and the amount and location of erosion due to various mechanisms. Mass movements appearing to have displaced more than about 0.76 m^3 of soil were individually surveyed. Those portions of all gullies having cross sectional areas greater than about 930 cm^2 were also surveyed. Ground conditions and rill erosion were estimated from transects running across the slope at 40 m intervals.

RESULTS

Sources of erosion

We measured 102 plots, nearly equally divided between public and private ownerships and between cable and tractor yarding. About one-third of the plots had supported old-growth redwood forest, and the rest had supported second-growth

redwood or similarly sized old-growth timber of other species. The plots averaged about 4.5 ha, including about 750 m^2 of road, 1400 m^2 of landing, and 3100 m^2 skid trails. The average plot age was about 4 1/2 years after logging. Erosion averaged 26.8 m^3/ha – a somewhat misleading value because we determined that measured erosion was best approximated by a log-normal distribution. The antilog of the mean of that distribution was 3.2 m^3/ha. The correlation between time-since-logging and estimated erosion was not statistically significant. Consequently, we assumed that the erosional impact of logging can be satisfactorily treated as a fixed amount and that it would be less correct to consider it as cubic meters per hectare per year based on time-since-logging.

None of the sites or mechanisms produced a majority of the erosion (Table 1). Nearly three-fourths of the erosion was in the form of gullies or slides. Among mechanisms, over 80 percent of the gully erosion was found on roads and skid trails, over 90 percent of the slump erosion on roads or landings, and over 80 percent of the slide erosion on those portions of the cut block not disturbed by roads, skid trails, and landings. Although these correlations between site and type of erosion make sense mechanistically, the actual percentages may owe much to the locations of the six largest erosional events measured. Each site/mechanism cell having more than 6 percent of the total erosion included at least one of those events.

REGRESSION ANALYSES

Evaluation of the Erosion Hazard Rating

The EHR is currently computed in the same manner for all proposed harvest areas, regardless of timber type or yarding method (although yarding method and erosion control practices are modified by it). Therefore, to test its efficacy as a predictor of post-logging erosion, the erosion measured at our plots was regressed against the EHR computed for the plots. The EHR proved to be a poor predictor; the squared correlation coefficient (the "explained variance") of 0.0095 suggests that less than 1 percent of the variability in erosion was related to variation in the EHR (the probability of obtaining a correlation coefficient of this size by chance alone is 0.83).

Next, we divided the data into four groups based on yarding method and timber type, and recomputed the regression (Table 2). Only the regression for 23 tractor-yarded old-growth redwood plots was statistically significant (r^2=0.63) (Datzman, 1978). The predictive capabilities of the equations for the other three groups were too limited to be of practical importance. Next, surface and mass erosion were each regressed separately against EHR. The resulting improvements were trivial. Lastly, erosion by each of the four processes (rills, gullies, slides and slumps) was regressed separately against EHR for each yarding and timber type combination. The only significant correlations were found in the group of tractor-yarded old-growth plots (Table 2). Nearly all old-growth

redwood stands in northern California have been cut and tractor yarding is gradually giving way to cable yarding on many sites. These results, therefore, suggest that the EHR will not be an accurate predictor of erosion in future timber harvests.

Predictions based on site and management variables

Next, we wanted to determine if there were relationships within the data that could be used to estimate erosion. Variables were screened by considering regressions on all possible subsets of variables. After several iterations, we concluded that this equation - based on yarding method, slope, aspect, and geologic parent material - was the best predictor obtainable:

$$\text{Erosion } (m^3/ha) = .0125\ \text{SLOPE}^{1.297} \cdot \text{ASPECT}^{.696} \cdot \begin{matrix}\text{YARDING}\\ \text{FACTOR}\end{matrix} \cdot \begin{matrix}\text{ROCKTYPE}\\ \text{FACTOR}\end{matrix}$$

where YARDING FACTOR = 1.915 for tractor and .522 for cable; ROCKTYPE FACTOR = .275 for ultramafic, .518 for granite, .590 for Franciscan, 1.682 for metamorphic, 1.908 for hard sedimentary, 3.703 for soft sedimentary.

This equation had a squared multiple correlation coefficient of 0.43 and an adjusted multiple correlation coefficient (Seber, 1977) of 0.38. The standard error of estimate was 0.64 log units. The regression was highly significant statistically, as were the partial regression coefficients for yarding method, slope, and aspect, and the multiple correlation coefficient between geological variables and the dependent variable.

The use of a logarithmic regression to estimate erosion seems the appropriate way to address two aspects of our data. First, the distribution of plot erosion was approximately log-normal. Second, the effect of a few extreme values (six erosional events, four plots) on the computed regression coefficients was reduced.

DISCUSSION

In comparing the results to other investigations, the experimental design of our study should be kept in mind. Most frequently, investigators attempt to hold constant as many variables as possible in order to observe unambiguous relationships between erosion and the variables studied. Our study was less tightly controlled. Yarding method and operator performance interacted with site variables in the usual fashion. The term "operator" refers to all aspects of planning and execution of a timber harvest that affect the subsequent erosion. This interaction may, in some cases, make interpretations of the results more difficult, but we concluded that the experimental design produced coefficients that more accurately portray how erosion is related to the independent variables in ordinary logging operations (Fig. 1). By not controlling operator performance, we obtained an indication of how much erosion related to timber harvest may be affected by differences in operators. Not all of the unexplained variability could be eliminated by including variables that define operator performance. We do have, however, several

indications that operator behaviour may account for much of the inability of our equation to predict erosion.

We revisited the four plots which had the highest erosion rates to verify the accuracy of the measurements and to determine why so much erosion had occurred. At one, we found that a landing had been constructed by using fill material obtained by cutting away the toe of an incipiently unstable rotational failure. At the second plot, runoff had been diverted from a haul road to either edge of a deep road fill. At the third site, the failures were apparently due to excessive subsurface drainage to a steep clearcut area. The original harvest and subsequent control burn had so churned up the ground that none of the confirming landmarks could be found at the presumed site of the fourth plot. However, we did note enough erosion for it to have been the plot. The original survey had recorded 19 separate major erosional events.

In addition to on-site inspections, we compared these four plots with the other 98. Using the equation as a guide, we estimated that the average erosion on the four plots should have been about three times the average erosion on the 98 plots. Instead, the observed difference was about 56 times the average erosion.

Although none of the results clearly demonstrate that operator differences are as large a source of variation in erosion as site differences, we believe that the evidence points in that direction. We suspect that most operators are being careful on sites which they perceive to present high erosion hazard. Conversely, they may be more relaxed

on sites with low apparent erosion hazard. This difference would tend to reduce the correlation between site variables and subsequent erosion. If our interpretation of these data is correct, the mere fact that an erosion hazard rating has a low correlation with subsequent erosion does not necessarily mean that it is an ineffective predictive tool. If, as intended, the rating modifies operator performance, it should decrease the correlation between erosion and the rating.

What was the effect of each variable on logging-related erosion? Slope varied from 10 percent to 85 percent within our data. The coefficient of slope indicate that erosion should be nearly 16 times greater on the 85 percent slope than on the 10 percent slope (Fig. lA). Similarly, erosion on southerly slopes should be 4.25 times greater than on northerly slopes and westerly slopes would be expected to be about 17 percent more erodible than easterly slopes (Fig. 1B). Shifting from tractor yarding to cable yarding could reduce erosion by 73 percent (Fig. 1C). Lastly, differences in geologic parent material are associated with a 13-fold difference in erosion (Fig. 1D). Confidence in the estimated effects must be tempered by concern over the unknown effect that their lack of independence may be causing.

CONCLUSION AND RECOMMENDATIONS

The Erosion Hazard Rating now used in California's Coast Forest District is a poor predictor of post-logging erosion. It was significantly correlated only with erosion associated

with tractor harvest of old-growth redwood. The equation developed in this study is superior to the EHR because it more closely correlated with subsequent erosion, and, in addition, it provides a quantitative estimate of expected erosion.

Operator performance may be as great a source of variation in logging-related erosion as are site characteristics. We recommend, therefore, that future investigations focus attention on how logging is carried out and not be restricted to relating erosion to only site characteristics.

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Table 1. Distribution of logging-related erosion among erosional mechanisms and sites

Erosional Mechanisms	Sites				
	Roads	Landings	Skid Trails	Other	Total
	Percent				
Rills	1.0	1.2	3.7	2.1	7.9
Gulleys	17.8	3.8	12.1	3.1	36.8
Slides	1.8	2.0	2.3	30.4	36.4
Slumps	6.7	10.7	1.0	0.4	18.8
Total	27.2	17.6	19.2	36.0	100.0

Table 2. Coefficients of determination (r^2) for regression of erosion one Erosion Hazard Rating, by yarding method, and timber type

Yarding method and timber type	Plots	Type of erosion				
		Rills	Gully	Slide	Slump	Total
		.....r^2.....				
Cable-old growth	12	0.00	0.23	0.22	0.12	0.11
Cable-other types	43	0.02	0.03	0.02	0.02	0.02
Tractor-old growth	23	0.07	0.66*	0.48*	0.30*	0.63*
Tactor-other types	24	0.02	0.11	0.08	0.02	0.06

* Statistically significant $p < 0.01$.

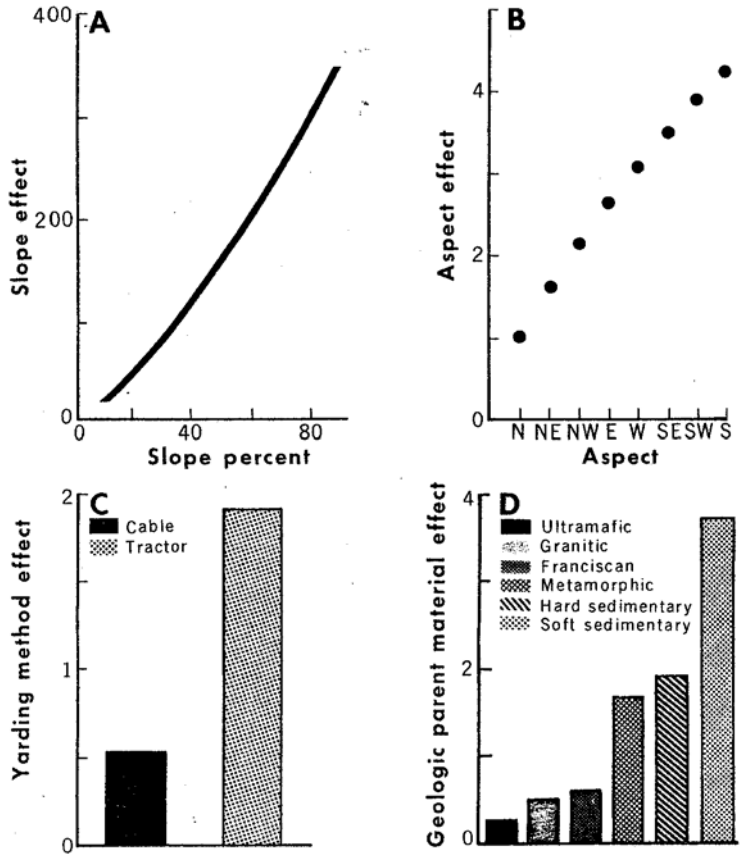

FIGURE 1. Multiplicative effects of slope, aspect, yarding method, and geologic material on logging-related erosion in northwestern California.