EROSION AND SOIL DISPLACEMENT RELATED TO TIMBER HARVESTING IN NORTHWESTERN CALIFORNIA, U. S. A.

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SUMMARY

The relationship between measures of site disturbance and erosion resulting from timber harvest was studied by regression analyses. None of the 12 regression models developed and tested yielded a coefficient of determination (R^2) greater than 0.60. The results indicated that the poor fits to the data were due, in part, to unexplained qualitative differences in disturbance associated with cable and tractor yarded harvests. Improved prediction might be achieved by weighting each elementary area of disturbance by the sine of its slope for estimates of surface erosion and by both the sine of its slope and its cut bank height for estimates of mass erosion.

KEYWORDS: logging, erosion, site disturbance, regression

INTRODUCTION

A good vegetative cover can help prevent erosion by reducing raindrop impact and by impeding overland flow. It also creates a litter layer that can protect the soil surface and promote infiltration. It has long been assumed that the amount of erosion from an area would be proportional to the amount of bare ground or to the degree of site distur bance. Accordingly, many investigators have used the percentage of bare ground or some other areal index of disturbance as an indicator of the potential for erosion or site damage (Dickerson 1968, Rice and Wallis 1962, Ruth 1967, Swanston and Dyrness 1973). Some investigators have gone further and separated the total bare area into qualitative categories depicting different levels of disturbance (Garrison and Rummel 1951, Patric and Gorman 1977, Wooldridge 1960). Only a few, however, have attempted to relate bare area or disturbance to measured erosion or sedimentation (Haupt and Kidd 1965; Rice, et al 1979; Rice and Wallis 1962). Even in these latter investigations, the relationship between disturbance and erosion or sedimentation was qualitative, ambiguous, or both.

In a study of cable and tractor logging in northwestern California, the amount of logging-related disturbance was not a good predictor of erosion (Rice and Datzman 1981). Data from 102 plots showed that erosion was best predicted by an equation that included slope, aspect, yarding method, and geologic parent material. The prediction equation was, however, not precise (R^2 = 0.43). The lack of precision was attributed chiefly to unmeasured qualitative differences in how the various timber harvests they sampled were conducted.

This paper reports a study of the relationship between erosion and different descriptors of site disturbance associated with logging. Our purpose was to observe how various disturbance variables were related to each other and, especially, to different types of erosion, in northwestern California. The data collected by Rice and Datzman (1981) provided the basis for the work.

EXPERIMENTAL METHODS

In this study, we defined "erosion" as the volume of voids created by rills, gullies, and mass movements. We found that we could not accu rately estimate the amount of deposition within the study plots. Consequently, we decided to use void volume as the estimate of erosion rather than to contaminate those relatively accurate data by subtracting estimates of deposition which had low precision and accuracy. We made no attempt to measure sheet erosion, and therefore, that omission compensated to an unknown degree for our ignoring deposition.

Field Procedures

A stratified sampling scheme was used to obtain maximum utility from the data collected. The strata included four slope classes, five annual rainfall classes, six geologic types, three lengths of time-since-logging, and two yarding methods. Plots were selected so as to get a uniform distribution of plots across all strata. This sampling method yielded acceptably low ($r < 0.70$) correlations between the five stratification variables.

The landing was the locus of each plot. The 102 plots were rectangular, about 200 m wide, and extended up or down the slope to include all area from which logs were yarded to a particular landing. They also extended 40 m from the landing in the opposite direction from which the logs were skidded. Logs were skidded downhill on almost all tractor yarded plots. Logs were yarded uphill on all cable yarded plots.

Rill erosion and some independent variables were estimated from data collected on transects extending across the slope at 40-m intervals (Table 1). Mass movements appearing to have displaced more than about 0.76 m^3 of soil and those portions of gullies having cross-sectional areas greater than 930 cm^2 were surveyed individually.

The 102 cutover plots we studied were about equally divided between public and private ownerships and between cable and tractor yarding. About one-third of the plots had supported old-growth redwood forests, 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, 1,400 m^2 of landing, 3,100 m^2 of skid trails, and about 21 percent bare ground. On the average, the timber harvest had displaced 167 m^3/ha of soil and resulted in an erosion rate of 26.8 m^3/ha--somewhat misleading values because we determined that erosion and soil displacement were best approximated by log normal distributions. The associated medians of soil displacement and erosion are 8.5 m^3/ha and 3.2 m^3/ha, respectively. The average plot was measured 4 1/2 years after the harvest. The correlation between time-since-logging and estimated erosion was not statistically significant ($\alpha = 0.4$). Consequently, we assumed that the effect of logging on erosion can be satisfactorily treated as a fixed amount and that it would be less correct to consider it as m^3/ha/yr based on time-since-logging.

Regression Analyses

All analyses were done by regression techniques using logarithmic transformations of the data. A logarithmic regression model was preferable to an additive model because the erosion data were log-normally distributed, the regression residuals were also approximately log-normally distributed, and a multiplicative model seems to be a closer approximation to natural interactions among variables. Furthermore, in all regressions, the logarithmic model was a better predictor of erosion than one based on untransformed data.

The 12 analyses were conducted using an all-possible subsets regression (Dixon and Brown 1979). Our criterion for selecting "best" regression equations was minimum Mallows' Cp (Daniel and Wood 1971). The Cp statistic facilitates comparison of regression models having different degrees of freedom. The best regression is the one whose residual sum of

Table 1. Independent variables investigated in regression analyses relating logging-associated erosion to site conditions.

Variables	Definition
Site Variables:	
GEOLOGY	A set of five dichotomous variables indicating which of six broad classes of geologic parent material (soft sedimentary formations, hard sedimentary formations, metamorphic formations, the Franciscan formation, granitic formations, and ultramafic formations) underlay the plot.
SLOPE	The tangent of the average slope gradient of the plot.
ASPECT	The average orientation of the plot as indicated by an arbitrary scale .having a minimum value of 1.0 for northerly aspects, and a maximum value of 8.0 for southerly aspects.
AGE	The elapsed time between when the plot was logged and when our measurements of erosion were made.
ELEVATION	The altitude of the plot above mean sea level.
RAINFALL	Mean annual precipitation at the plot as determined from isohyetal maps (Rantz 1968).
SURFACE CLAY	The percent of particles < 2 μ in diameter in the surface 15 cm of mineral soil.
SURFACE SAND	The percent of particles with diameters between 0.2 mm and 2 mm in the surface 15 cm of mineral soil.
TWO-YEAR, SIX-HOUR 1/	The maximum six-hour rainfall amount expected to occur in a two-year period based on isohyetal maps (U.S. Dep. Commerce, Weather Bureau 1956).
SURFACE AGGREGATE 1/ STABILITY	A numerical index of the stability of an undisturbed soil sample when subjected to a fine stream of water sprayed from a distance of 40 cm. (U.S. Dep. Agric., F.S., 1976).

SUBSURFACE AGGREGATE STABILITY 1/	A numerical index of the stability of an undisturbed soil sample when subjected to a fine stream of water sprayed from a distance of 40 cm.
SURFACE DISPERSION RATIO.1/	The ratio of hydrometer readings for dispersed and aggregated soil samples (Middleton 1930).
SUBSURFACE DISPERSION RATIO 1/	The ratio of hydrometer readings for dispersed and aggregated soil samples (Middleton 1930).

Disturbance Variables:

METHOD	A dichotomous variable indicating whether tractors or a cable system was used to haul logs from where they were cut to the landing.
LANDING	The proportion of the plot used for loading logs onto trucks for transportation from the forest. Includes associated cut and fill slopes as well as loading area.
SKID TRAILS	The proportion of the plot's planemetric area occupied by paths or trails used to drag logs from where they were cut to the landing.
DISPLACED SOIL	The volume of soil displaced by the construc tion and use of skid trails (m^3/ha).
COMPACTION	The sum of the proportions of the plot in Roads, Landings and Skid Trails.
BARE 1/	The percent of the plot having exposed mineral soil at the time of our survey.
ROADS 1/	The proportion of the plot containing the running surface and associated cut and fill slopes of a road.
BURNED 1/	A dichotomous variable indicating whether or not the plot had been broadcast burned after the timber harvest.

1/ Variables failing to be included in any of the regression models having minimum Mallows' Cp.

squares is the least after being adjusted for the number of variables in the model.

We investigated the effectiveness of eight different site disturbance variables as predictors of erosion (Table 1): six quantitatively described some component of land disturbance associated with logging, and two indicated qualitatively whether the plot had been tractor- or cable-yarded and whether it had been broadcast-burned after yarding. In addition to the site disturbance variables, each regression analysis tested 12 site variables describing the slope, aspect, elevation, precipitation regime, geologic parent material, soil, and the elapsed time between the timber harvest and our measurements (Table 2).

Twelve regression equations were computed (Table 2). In each, BARE and BURNED and the Site Variables were tested for possible inclusion in best models. In the first three regressions (models 1, 5, and 9), disturbance was described by using the individual descriptors: ROADS, LANDINGS, and SKID TRAILS. In the next three (models 3, 7, and 11), disturbance was described using the aggregated descriptors: DISPLACED SOIL and COMPACTION. The volume of surface erosion, the volume of mass erosion, and the total volume of erosion were regressed against these variables. These six regression models were then reanalyzed with METHOD added for possible inclusion in addition to the two groups of disturbance variables models 2, 6, 10, and 4, 8, 12).

Lastly, each of the excluded Disturbance Variables was regressed against the set of independent variables included in each of the 12 models. We wanted to see if the poor performances of some of the Disturbance Variables were caused by collinearity. It seemed plausible that if one of the Disturbance Variables was highly correlated with a set of the other independent variables, either it or its correlates would be excluded from the best equation predicting erosion.

RESULTS

All of the regression analyses produced equations which were relatively poor predictors of erosion (Table 2). Disturbance Variables contributed the greatest proportion of the explained variation (R^2) in those equations predicting surface erosion. The best prediction equations, however, were those estimating mass erosion. Even though the best equations usually included one or two disturbance variables, it often seemed that a variable was not really expressing the condition that its name implied; rather, that it owed its inclusion in the equation to some other site condition with which it was correlated. For example, LANDING is included in three best equations (Table 2, models 5, 6, 9). Its regression coefficient, however, carries a negative sign which is difficult to explain physically. Even though the relative increases in explained

Table 2. Regression models relating components of logging associated erosion to site and disturbance variables 1/

Independent Variables	Dependent variables and model numbers											
	Surface erosion				Mass erosion				Total erosion			
	1	2	3	4	5	6	7	8	9	10	11	12
	........................Standardized Regression Coefficients..........................											
Site Variables												
GEOLOGY 2/	0.29	0.32	0.26	0.30	0.40	0.40	0.63	0.38	0.37	0.35	0.46	0.35
SLOPE	0.28	0.31	0.25	0.30	0.45	0.47	0.21	0.44	0.28	0.30	0.22	0.30
ASPECT	0.30	0.25	0.29	0.25	0.22	0.12	0.26	0.16	0.33	0.29	0.31	0.29
AGE											0.17	
ELEVATION						0.16						
RAINFALL					-0.26	-0.25		-0.25				
SURFACE CLAY											0.15	
SURFACE SAND						0.16						
R^2 3/	0.22	0.22	0.22	0.22	0.41	0.41	0.41	0.41	0.35	0.35	0.38	0.35
Disturbance variables												
METHOD		0.43		0.36		0.45		0.65		0.37		0.37
LANDING					-0.25	-0.23			-0.14			
SKID TRAILS	0.36				0.32				0.29			
DISPLACED SOIL			0.16	0.14							0.18	
COMPACTION			0.26					-0.30				
R^2 4/	0.30	0.33	0.32	0.34	0.52	0.56	0.41	0.52	0.42	0.43	0.41	0.43

1/ Computed by using the logarithms of the continuous variables.
2/ Highest standardized regression coefficient among the geologic variables.
3/ Coefficient of determination for model including only Site Variables.
4/ Coefficient of determination for complete model.

variation due to the inclusion of the Disturbance Variables was occasionally substantial, based on their standardized regression coefficients, Disturbance. Variables were less accurate as predictors of erosion than the Site Variables in most cases.

A11 prediction equations that included METHOD among the independent variables were improved (Table 2; models 2, 4, 6, 8, 10, 12). Its presence in the prediction equations usually led to the exclusion of some or all of the disturbance variables which had previously been included (Table 2; models 1, 3, 5, 7, 9, 11). For example, its presence in model 2 led to the exclusion of SKID TRAILS, which had appeared in model 1 (Table 2). In one case, model 8, its presence led to the inclusion of COMPACTION in the equation. Except in model 6, METHOD always had the largest standardized regression coefficient of any variable in the equations. This suggests that, in our data, erosion rates are separated into two distinct groups based on yarding method.

Our investigation of possible collinearity among the Disturbance Variables showed them to fall into three categories. The first category (BARE, BURNED, ROADS) included variables which were only weakly correlated with all variables tested. They never appeared in one of the best equations and usually had weak multiple correlations with the independent variables included in each of the best equations. The coefficients of determination of BARE, when regressed against the independent variables included in the 12 equations, ranged from 0.13 to 0.34. The coefficients of determination for BURNED ranged from 0.26 to 0.42, and for ROADS they ranged from 0.02 to 0.29. LANDING and DISPLACED SOIL made up the second group of variables. They were occasionally included in the best equations, but otherwise showed low coefficients of determination with the included independent variables. The last three variables, METHOD, SKID TRAILS, and COMPACTION were highly correlated. Consequently, when any one of them was included in a best equation, the other two were excluded and had high (>0.70) coefficients of determination with the included variables. Model 8 is the only exception to this rule.

DISCUSSION

The efficacy of the variable METHOD as a predictor of erosion suggests that the site disturbances created by the two yarding methods differ. Bare ground, for example, created by tractor skidding is apparently related to erosion differently than bare ground created by cable yarding. Similarly, the proportions of a plot occupied by roads, landings, or skid trails are inadequate descriptors of the effects of those types of disturbance on subsequent erosion. In retrospect, it appears to us that mere areal or volume descriptors are not an effective way to describe the influence of logging disturbance on erosion. Most soil conservation practices used on agricultural land do not involve changes in the amount of disturbance. Rather they address the pattern of disturbance--for example, contour farming changes the configuration of disturbance with respect to the prevailing land slope. Patterns of disturbance in logged areas are usually more complicated than those encountered in agriculture. It may not be possible, therefore, to address the pattern directly, but it should be possible to weight measures of disturbance so that their values are more closely related to the physical processes they are describing.

In general, for a given depth of surface flow, the eroding force per unit length and width of hillslope surface is proportional to the sine of the hillslope gradient (Norton 1945). This simple relationship between the component of gravity acting on a soil surface and the erosion of that surface has been used successfully to model erosion by surface processes (Nash 1980). The sum of all the disturbed areas on a plot, with each area being weighted by the sine of its slope, should be an effective predictor of surface erosion. If mass erosion were being predicted, a plausible modification might be to weight each disturbed area by its cutbank height as well as the by sine of its slope.
Such a weighting would be an approximation of each disturbance element's potential for leading to mass instability.

These weighting systems and the separate prediction of surface ero sion and mass erosion may improve our ability to describe and predict the effect of timber harvests on erosion. Whether these improvements will be sufficient to make measures of disturbance useful for predicting erosion is uncertain. Much variation may remain unexplained because of un measured differences in how the harvests are carried out (Rice and Datzman 1981). The existence of such "sociological" determinents of erosion may always limit the prediction capability of regression analyses.

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ZUSAMMENFASSUNG

Die Beziehung zwischen Standorts-Störungs-Merkmalen and Erosion infolge Holzbringung wurde durch Regressions-Analysen studiert. Neun der zwölf entwickelten and getesteten Regresions-Modelle lieferten einen Bestimmungs-goeffizienten (R^2) gröβer als 0,6. Die Resultate zeigten, daβ die geringe Übereinstimmung der Daten zum Teil durch unerklärte qualitative Störungs-Unterschiede von Seil- oder Traktor-Bringung begründet waren. Eine verbesserte Voraussage kann erhalten werden durch eine Gewichtung jeder elementaren Störungseinheit (nach dem) durch den Sinus seiner Hangneigung um die Oberflächenerosion abzuschätzen and durch den Sinus seiner Hangneigung and seiner Anschnittshöhe um die Massenerosion zu bestimmen.

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