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Predicting landslides in clearcut patches

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ABSTRACT Accelerated erosion in the form of landslides can be an undesirable consequence of clearcut logging on steep slopes. Forest managers need a method of predicting the risk of such erosion. Data collected after logging in a granitic area of northwestern California were used to develop a predictive equation. A linear discriminant function was developed that correctly classified almost 90% of the data. The equation was based on measurements of slope, crown cover, tributary drainage area, and distance from a stream. A procedure was then developed by which the discriminant function can be used to determine the optimum strategy for managing landslide-susceptible terrain.

INTRODUCTION

Landslides are a critical problem for forest managers in areas having steep slopes, unstable soils, and high rainfall. In parts of the western United States, many forested slopes that were harvested by the clearcutting method have since failed (Gonsior & Gardner, 1971; Swanson & Dyrness, 1975; Swanston, 1970; Bishop & Stevens, 1964).

Landslide prediction has been accomplished in chaparral areas of southern California. Physiographic and vegetative variables were subjectively evaluated from small-scale aerial photos by Kojan *et a1.* (1972). They successfully predicted landslide placement for 84.4% of the study area (Santa Ynez-San Rafael mountains near Santa Barbara, California). Similar accuracy was achieved in the San Gabriel mountains using their procedures (Foggin & Rice, 1979). In two other studies, linear discriminant functions (Fisher, 1936) were used to distinguish between sites which did and did not slip (Rice *et a1.,* 1969; Rice & Foggin, 1971).

This paper reports a study in northwestern California that developed a method for predicting the risk of landslides after clearcutting on granitic terrain.

STUDY AREA

The study area is in the southeast part of the English Peak Batholith,

in the drainage basin of the Little North Fork, Salmon River. Most of the slopes are covered by residual and transported soil derived from coarse crystalline granitic rock. The bedrock ranges from unweathered to completely weathered. Altitude ranges from 700 to 1000 m. The slopes of 60-80% are commonly 100 m or more in length. Mean annual precipitation ranges from 1000 to 1200 mm, with 90% of the precipitation occurring between October and March, primarily as rain. The average merchantable timber volume is 292 m^3 ha^{-1}.

Eleven patches on granitic soils in the basin were clearcut between 1967 and 1970. During winter 1972, two storms having return periods of about 20-25 years caused severe landsliding (Fig.l). In

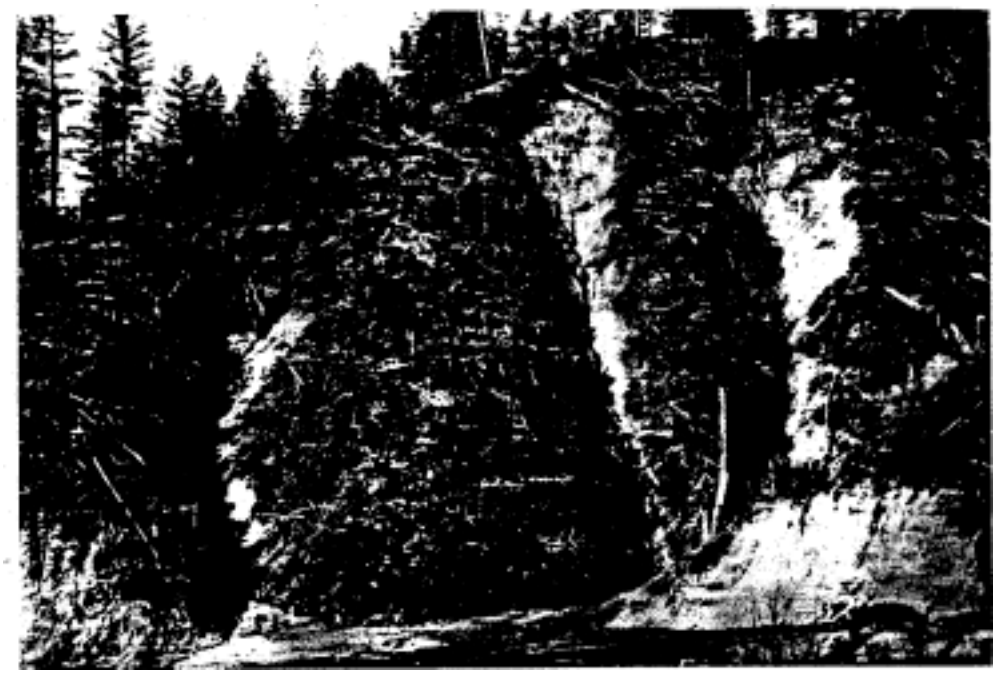

FIG.1 Landslides occurred in blocks logged by clearcutting in the Little North Fork drainage of the Salmon River, California, during winter 1972.

January, a three-day storm yielded 235 mm of precipitation; a second storm in March produced 155 mm of precipitation in two days. The storms triggered 102 debris avalanches in 122 ha of clearcut patches. The avalanches eroded 32 344 m^3 of soil and scarred 3.31 ha. Individual slides ranged in size from 16.3 to 634.8 m^2 and eroded between 8.3 and 580.7 m^3 of soil.

We limited the analysis to the granitic rock type, since virtually all the damage occurred on that type. A 62 ha area chosen for intensive investigation was selected because it was readily accessible, landslides were prevalent, and it contained a representative sample of site. variables presumed to be critical. Parent material in the study area only spanned a portion of the range of weathering classes (Durgin, 1977), ranging from partially

weathered material with residual unweathered core stones or blocks to completely weathered granitoid (grus). No slides were observed in areas underlain by more completely weathered material. All slides included in this study were on hillslopes and were unaffected by roads or streambank cutting.

METHODS

Study sites were classified as unstable (landslide sites) or stable (non-landslide sites). A grid of 66 points (spaced 61 m x 61 m) was used to characterize the stable sites. The grid was located randomly, but with the restriction that no point fell on a slide. Unstable areas were characterized by the conditions at the 68 slides in the study area. In this fashion, we could test how unstable sites differed from stable sites.

Landslide volumes were surveyed in the field. Five physiographic and two vegetative variables were measured from aerial photographs for use in developing the landslide prediction equation (Table 1). Later, two geologic variables were added in an attempt to improve the equation.

Most variables were measured on 1:6000 scale aerial photos taken in 1974. The slopes of slide sites were measured on post-logging 1971 photographs at a scale of 1:15 840 and the vegetative variables were estimated from 1964 photographs at the same scale. A stereocomparator was used to measure landslide and terrain features. Photo image coordinates were not corrected by ground control because both prior work (Simonette *et a1.*, 1970; Kojan *et a1.*, 1972; Rice *et a1.*, 1969) and our own investigations concluded that uncorrected data could be effectively used.

DISCRIMINANT ANALYSIS

A linear discriminant function was used to formulate an equation to classify sites as stable or unstable. A linear discriminant function projects the original sample points onto a new line oriented to provide maximum separation between the two samples. A successful discriminant analysis provides the basis for a function which can estimate the relative stability of new (previously unmeasured) sites before clearcutting. A large number of possible discriminant functions were computed. The better equations were subjected to split sample testing (BMDP9R, Dixon & Brown, 1979) and "jacknifed" classification tests (BMDP7M, Dixon & Brown, 1979).

Our final equation was chosen because of its consistency under the two tests and .its high overall classification accuracy of 89.6%. It successfully classified 86.4% of the stable sites and 92.6% of the unstable sites. The discriminant function chosen had a logarithmic form:

$$x = 13.24 - 4.63 \log(SLOPE) - 3.04 \log(DOM) - 1.03 \log(HORSTM) + 0.69 \log(DRAREA) \quad (1)$$

TABLE 1 Variables measured at stable and unstable sites in Little North Fork drainage basin, northwestern California, USA

Variable	Definition	Stable sites (n = 66)			Unstable sites (n = 68)		
		Min.	Mean	Max.	Min.	Mean	Max.
PHYSIOGRAPHIC*							
SLOPE (pct.)	Slope angle between foot and head scarp of landslide	6.0	41.5	83.0	37.0	63.9	95.0
ASPECT (deg.)	Smallest angle from south to the axis of landslide	0.0	93.8	180.0	16.0	103.7	177.0
HORRID (m)	Horizontal distance from slide scarp to ridge	0.0	36.2	186.7	0.6	30.1	135.9
HORSTM (m)	Horizontal distance from slide scarp to stream	0.0	47.2	304.8	0.0	39.2	167.6
DRAREA (m^2)	Tributary area above landslide scarp	0.0	645.3	2554.8	3.3	209.5	2448.3
VEGETATIVE							
DOM (pct.)	Crown cover of dominant trees 0.405 ha circular plots	5.0	62.9	100.0	40.0	87.4	100.0
UNDER (pct.)	Understory on 0.405 ha circular plots	0.0	23.3	80.0	0.0	4.5	20.0
GEOLOGIC							
WXA†	Variables defining the degree of	-1.6	0.3	1.0	-1.6	-0.3	0.0
WXB†	bedrock weathering (Durgin, 1977)	-7.0	0.3	1.0	-7.0	-0.3	1.0
QTX (pct.)	Quartz in the parent material (Sefert, 1974)	2.5	6.4	10.0	2.5	6.5	10.0

* The grid intersection was the origin of measurement for stable sites.
† These dummy variables define the site location with respect to three weathering classes.

in which x is the discriminant value (canonical variable), with positive values indicating stability. The mean discriminant value for the stable sites was 1.17. For the unstable sites it was -1.14.

The relative importance of slope identified in this study agrees with research reported earlier (Rice *et al*., 1969; Swanston, 1970). The variable DOM (crown cover of dominant trees) integrates biologic and edaphic characteristics of the forest ecosystem. Paradoxically, in spite of the fact that tree roots provide structural support for soils, the density of dominant timber was positively correlated with instability. Apparently, this correlation was due to the following factors; firstly, the timber may be indexing high moisture conditions and greater probability of high pore water pressures which might promote slope failure; secondly, slopes with heavy forest cover may be more dependent upon the structural support of tree roots to maintain their stability; and thirdly, they may have been more dependent on transpiration to dispose of excess soil water than slopes with lighter stands. We believe the first two reasons probably dominated the relationship.

The roles in equation (1) of two variables, namely, horizontal distance to the stream (HORSTM) and drainage area (DRAREA), are a little more obscure. Logic would seem to indicate that proximity to a stream would be correlated with landslide occurrence, because of the possibility of higher pore water pressure. Similarly, large drainage areas would be expected to be correlated with high pore water pressures and, therefore, landslide occurrence.

In our equation, the opposite condition seems to prevail. Slides are more likely at sites distant from streams and having small drainage areas. The two variables, therefore, may be identifying steep slope facets as landslide sites. The location of the slides visible in Fig.l is fairly typical; most slides occurred at the tops of small ephemeral drainage lines. An investigation in coastal Oregon suggests that the location of the slides in the Little North Fork may be typical of failures after clearcutting and not a peculiarity of our study (personal communication: George Bush, soil scientist, Siuslaw National Forest). Investigators found a preponderance of their slides concentrated in the "headwalls" of first order drainage basins. Equation (1) can be interpreted to mean that the most likely site for a debris avalanche after clearcutting is on a steep slope facet at the upper end of a small drainage basin which supported heavy timber before logging.

According to Bayes' theorem, the posterior probability (P) of a slide occurring, given a particular discriminant value (x), is determined by:

$$P(\text{slide}|x) = \frac{P(x|U)\pi_u}{P(x|U)\pi_u + P(x|S)\pi_s} \qquad (2)$$

where

π_u prior probability of an unstable site as determined by the proportion of the study area in slides;

π_s 1 - π_u is the prior probability of a stable site;

x computed value of discriminant function from equation (1);

U the probability distribution of x's for the unstable sites in the developmental data;

S the probability distribution of x's for the stable sites in the developmental data.

Discriminant analysis may appear to be of limited use because the posterior probability assigned to the average slide site is only 0.28 (Fig.2), but debris avalanches never involve a large proportion of the landscape. A better way to measure the efficiency of the analysis is to consider the relative improvement in risk evaluation achieved by its use. Relative landslide risk can be computed by dividing the probability of a slide estimated using the discriminant function by the prior probability of slide (Fig.2). Considered in this fashion, the average slide site in the Little North Folk study was 10 times more likely to be unstable than the average terrain in the study area and about 150 times more likely to fail than the average of the stable sites.

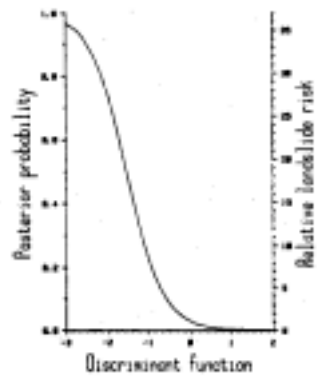

FIG.2 Probability that landslides will follow clearcut logging on granitic terrain as estimated using equation equation (1) and equation (2).

Strictly speaking, the probabilities computed by equation (2) apply only to areas having the same geology, topography, forest cover, logging history, and climate pattern. It is unlikely that a forest manager will experience an exact duplication of the conditions at Little North Fork. Many situations, however, may be sufficiently similar so that managers can use our experience as a guide.

SITE STABILITY ANALYSIS

The ability to estimate landslide hazard, while helpful, does not fully resolve the land manager's problem. The manager must decide the relative importance of various correct and incorrect site classifications. The possibilities of classification are: A - correctly identifying a stable site, B - incorrectly identifying a stable site as unstable, C - incorrectly identifying an unstable site as stable, and D - correctly identifying an unstable site.

Once the decisions have been reached, a "payoff" function can be computed which is a linear combination of the conditions listed:

$$Y = aA + bB = cC + dD \tag{3}$$

in which Y is a number which integrates the penalties and benefits that are derived from the various correct and incorrect predictions and a, b, c, d are coefficients selected to weight the importance of conditions A, B, C, D, which are the proportions of correct or incorrect predictions.

Considering the correct identification of a stable site (condition A) as having a positive value of +1, incorrectly classifying a stable site as unstable (condition B) might have a value of -1. The penalty is modest since no environmental damage results and, conceivably, the error can be corrected in the next cut. Incorrectly, calling an unstable site stable (condition C) might carry a heavier penalty, say -5, since environmental damage is likely to result. The greatest reward, +25, is associated with correctly identifying an unstable site (condition D). This condition permits utilization of the timber resource without adverse environmental consequences.

In addition to evaluating various costs and benefits, the manager must decide what probability level (P) will be considered to be an unacceptably high risk of slope failure. That decision can be aided by using the subjective weights for equation (3) and computing the effect of various probability levels which might be used as criteria. For example, if the proportion of the area classified as unstable under probability level P is U_p and the proportion considered stable is S_p, equation (3) would read:

$$Y = aP_sS_p + b(1 - P_u)U_p + c(1 - P_s)S_p + dP_uU_p \tag{4}$$

where P_s is the proportion of S_p that is actually stable and P_u is the proportion of U_p that is actually unstable. Since these proportions are unknown they must be estimated. Using the distribution of posterior probabilities (Fig.2) and the sample of x's from the area under investigation, P_s is assumed to be the posterior probability corresponding to the average of the x's in S_p and P_u is similarly defined.

As an example: Suppose that the manager is evaluating the possible effect of clearcutting on a particularly sensitive 5 ha block and is considering using a probability level of 0.6 as the cutoff point. By sampling within the proposed cutblock, the manager determined that 4 ha would be classified non-hazardous and 1 ha would be classified hazardous. P_s and P_u are estimated to be 0.3 and 0.8 respectively. By entering this information into equation (4) and using the subjective weights we proposed, the payoff function can be computed:

$$Y = (1 \times 0.7 \times 0.8) + (-1 \times 0.2 \times 0.2) + (-5 \times 0.3 \times 0.8) + (25 \times 0.8 \times 0.2) = 3.32 \tag{5}$$

As an alternative, the manager considers elevating the cutoff level to 0.7. At that cutoff level, Y = 1.20. As a third alternative, the cutoff level is decreased to 0.5. At this probability level, Y = 3.05. In a similar manner, as many values of Y as seem feasible could be tested until the optimum is determined. If these three calculations were the only ones considered, the 0.6 probability level would be expected to be the most effective guide to hazard evaluation since it yields the highest value for the payoff function.

RECOMMENDATIONS

We recommend that forest managers use only the variables shown in equation (1). The other variables (Table 1), including the geologic variables, added little to the discriminating ability of the equation. The variables in equation (1) seem to represent the best balance between economy and accuracy for prediction of site stability in granitic terrain. Thus, in areas similar to the Little North Fork in climate, slope, vegetation, and soil, we suggest trying our equation and the resultant posterior probabilities as a guide for appraising landslide risk. Equation (1) should be verified in other igneous areas and, perhaps, in other geologic types to determine its applicability. If the area under consideration departs appreciably with respect to any of the important parameters (such as slope, parent material, climate, or cover type), the forest manager may be faced with the task of repeating our investigation in order to develop his own discriminant function. In either case, a discriminant analysis and the resultant probability function can be a useful tool for the objective evaluation of the debris slide hazard associated with timber harvests.

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