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Estimating Risk of Debris Slides After Timber Harvest in Northwestern California

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ABSTRACT

The risk of debris slides resulting from logging must often be appraised by foresters planning timber harvests. The Board of Forestry of the State of California commissioned the development of a Mass Movement Checklist to guide foresters making such appraisals. The classification accuracy of the Checklist, tested using 50 logging-related debris slides and 50 logged sites that had not produced debris slides, was correct at 60 sites in northwestern California. Its low accuracy is attributed to low variability of several constituent variables. Although the Checklist may be useful in distinguishing between generally stable and unstable areas, it is of little help in making site-specific decisions within a timber harvest area. The data collected to test the Checklist were used in a linear discriminant analysis to develop a three-variable equation to predict post-logging debris slide risk. It correctly classified 77 percent of the sites. Both analyses suggest that the relative debris slide risk associated with logging is best estimated using geomorphic variables which can change markedly over short distances and which are good surrogates for the forces affecting slope stability.

INTRODUCTION

Many slope stability problems must be dealt with and resolved by people who are not trained as engineering geologists. Debris slides resulting from forest management activities are one of those problems. In most circumstances the determination of debris slide risk and the appropriate response to that risk on private timberland in California is made by foresters. This paper tests the utility of two approaches to helping foresters in California manage slide-prone terrain: guidelines in the form of a checklist, and a linear discriminant function (Fisher, 1936).

Debris slides accomplish much of the erosional development of steep forested hillslopes of the western United States and other steep lands surrounding the Pacific Ocean. Because they are a normal part of the sequence of landscape evolution, naturally-occurring debris slides have been little studied. Even research concerned with the acceleration of sliding due to logging or roads is relatively recent. Although first noted in 1950 (Croft and Adams, 1950), most attention to the problem of logging-related mass wasting in the United States dates from the report (Bishop and Stevens, 1964) about post-logging debris avalanches in the Maybeso drainage of coastal Alaska. Other reports, on the 1964 flood in Oregon, soon followed (Dyrness, 1967; Rothacher and Glazebrook, 1968; Swanson and Dymess, 1975).

To control logging-related erosion, the State of California uses information about site and climate to determine which logging practices are appropriate. The Z'berg-Nejedly Forest Practice Act of 1973 mandated the drafting of new Forest Practice Rules (Green et al., 1981). The State Board of Forestry is charged with developing rules to guide timber harvest that will protect water quality and fish habitat, in addition to ensuring sustained yield of forest products. The rules are continually being revised as new information is obtained or new public concerns are expressed.

In 1981 the Board directed a task force to produce guidelines that would help foresters recognize mass movement risks. The guidelines were in the form of a Mass Movement Checklist (MMC; State Board of Forestry, 1981). The MMC, however, was never approved for use. Instead, the Board added definitions of "slide areas", "slide-prone areas", "unstable areas", and "unstable soils" to the Forest Practice Rules. The definitions of these terms were drawn from the MMC and the Rules require that they be addressed in Timber Harvest Plans. Consequently, our investigation remains relevant to today's practices even though the MMC is not being used directly.

OBJECTIVES AND SCOPE

In this paper, we first evaluate the effectiveness of the MMC to correctly classify sites that did and did not produce debris slides after logging. Second, we use data collected to test the MMC to test the hypothesis that an improved landslide risk evaluation methodology can be developed using a linear discriminant function (Fisher, 1936) based on local geomorphic characteristics. We use the general term "debris slide" to mean debris slides, debris avalanches, and debris flows as defined by Varnes (1958) and as used by Swanston (1969). We limit our analyses to slides associated with tree removal, eliminating those related to operating surfaces such as roads, landings, skid trails, and fire lines.

STUDY AREA

The study was conducted on the Six Rivers National Forest in northwestern California (Figure 1). The Forest extends 230 km (143 mi) south from the Oregon-California border (over 2° of latitude). Its western border is 10 to 60 km (6 to 37 mi) from the Pacific Ocean. Mean annual precipitation ranges from about 100 to 300 cm (40 to 120 in.; Rantz, 1968). The geology of the Forest is complex and heterogeneous. The varied collection of rocks combines with a rapid rate of uplift and a humid climate to produce some of the highest erosion rates in the country (Janda, 1979). The Forest encompasses two major geologic provinces-the Klamath Mountains Province in the north and the Coast Range Province in the south. They occur as a series of north-northwest trending belts (Irwin, 1966).

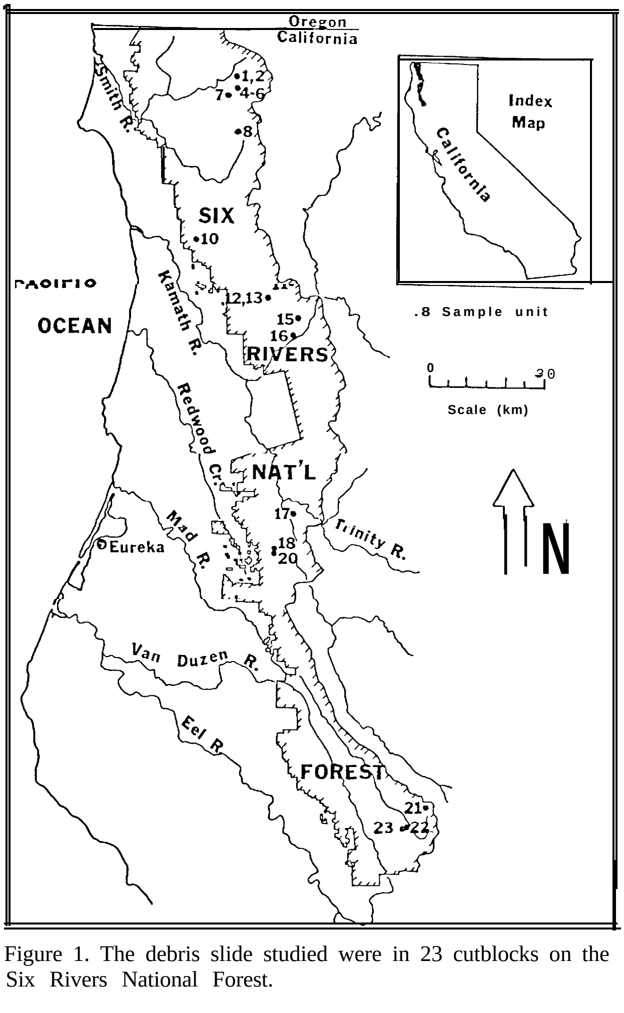

Figure 1. The debris slide studied were in 23 cutblocks on the Six Rivers National Forest.

The oldest belts form the Klamath Mountains Province. They are made up of a heterogeneous suite of ophiolites, eugeosynclinal sedimentary and volcanic rocks, and melanges. In turn, these have been intruded by Mid-Jurassic to Lower Cretaceous plutons and metamorphosed to at least the greenschist facies. The Galice Formation is the dominant rock unit in the western Klamath Mountains Province and underlies most of the northern half of the study area (Neely, 1981). It consists of mudstone and greywacke sandstone, with some volcanics, conglomerate, and chert. Steep streamside hillslopes in the Galice are often the site of shallow debris slides (Janda, 1979).

The Franciscan Assemblage is dominant in the Coast Range Province, which is in the southern half of the study area. It is made up of graywacke sandstone, shale, altered volcanic rocks, chert, minor limestone, and serpentinite (Bailey et al., 1964). Many of the rock types in this complex unit are intensely sheared and metamorphosed, resulting in high susceptibility to erosion and mass wasting.

METHODS

Selection of Sites

The debris slides we studied were located by Furbish (1981). Using high-altitude infra-red photographs, he first delineated general areas of the Forest where timber harvesting was taking place. There were 1,028 1-mi^2 sections within those areas. From these he randomly selected 24 sections containing at least one cable-yarded cutblock. The restriction to cable-yarded cutblocks is appropriate because the vast majority of harvest areas presenting mass movement problems will, due to the steep slopes, be cable-yarded. Of the 85 cutblocks found in the 24 sections he selected, only 23 contained at least one debris slide that was unrelated to operating surfaces, and therefore pertinent to our study. The remaining 62 either lacked slides or contained only slides that were related to roads, landings, skidtrails, or firelines. We succeeded in measuring 50 slides in 19 cutblocks of the 97 slides in 23 cutblocks investigated by Furbish. The remaining 47 were either inaccessible (41), not found (4), related to operating surfaces (l), or misidentified (1). Our sample, however, did not turn out to be much different from Furbish's. On average, our slide sites were $2^0 15'$ steeper and the control plots $1^0 18'$ flatter. The cutblocks were selected and debris slides identified using 1975 aerial photos. The slides were, consequently, at least 7 years old at the time of this study.

For each debris slide measured a control site was randomly selected from the cutblock containing the slide to give an estimate of the ambient condition of stable sites. The use of nearby control sites may have enhanced our ability to relate debris slide occurrence to geomorphic conditions. On the other hand, it greatly diminished our ability to relate debris slide occurrence to more gradually changing variables such as rock type or precipitation.

Although debris slides are often extensive features, the centroid of a slide where failure is initiated and the slide begins can usually be located accurately. The rest of the slide feature is either a zone of depletion caused by the erosive power of the slide mass or the zone of deposition. Therefore, each slide was characterized by measurements at its centroid and each control site was treated as the centroid of a potential slide.

When Furbish measured slide sites, he was primarily interested in steepland areas (inner gorge is a term often used by land managers in the Forest Service); that is, streamside hillslopes steeper than 30^o. This was because previous investigations (Farrington and Savina, 1977; Janda, 1979) had identified those areas as the source of most of the logging-related erosion problems. He found only 5 percent of the debris slides (representing 2 percent of the total slide volume) on non-steepland slopes. We included non-steepland areas in the control site selection because the MMC was designed for use on all types of terrain, not just steeplands.

Since the MMC was intended for State-wide use, it might have been more meaningful to select study sites throughout California. Practical and logistical considerations, however, limited our area of investigation to the Six Rivers National Forest. Because the preponderance of slope stability problems associated with logging in the state are in northwestern California, a successful MMC should be effective there. Nonetheless, our use of Furbish's data did bias our sample. Control sites, as well as slide sites, were considerably steeper than the distribution of forested slopes in northwestern California. The median slope in the forested areas of northwestern California is about 23^o. The median slope of our control sites was about 34^o. Our tests, therefore, are not indicative of the performance of the MMC throughout its intended range of application. Rather, they measure how useful the MMC would be in steeply sloping areas posing a high debris slide risk. Although our test is biased, the success of a MMC rests mainly on how effective it is in such an environment.

Quantification of Factors

The debris slide MMC consists of four quantitative primary factors and three qualitative secondary factors (Table 1). Each of the secondary factors consists of several related conditions. The MMC assumes that a potential for debris sliding exists if all four of the primary factor thresholds are exceeded. Secondary factors may modify conclusions tentatively reached based on the primary factors alone.

It was necessary to quantify the factors to make an objective test of the efficacy of the MMC. Quantification of the primary factors was straightforward; it was necessary only to provide a numerical scale for soil texture (Table 2). Soils having a textural code of 7 (fine sandy loams) or greater were considered noncohesive. The secondary factors, being more qualitative, were more difficult to quantify. We believe our interpretations (Table 2) reflect the essence of the descriptors of the MMC.

We also added four variables which we thought might be improvements over those contained in the MMC. Two, PRECIP2 and SLOPBRK2, were developed as possible substitutes for corresponding variables in the MMC. Two others had proved useful in similar studies: DISST (Rice and Pillsbury, 1982) and SUMDIS (Furbish and Rice, 1983).

Measurement of Variables

We visited each debris slide and control site during summer 1982. Whenever possible, variables were measured on the ground by surface inspection. Slope

Table 1. *Mass Movement Checklist (MMC) for debris slide potential (State Board of Forestry, 1981).*

Factors*	Criteria for Indicating Potential
A. Primary Factors:	
1. Slope Gradient	Greater than 65 percent slope.
2. Soil Mantle Depth	Less than 5 ft, including fractured rock overlying hard bedrock.
3. Soil Texture	Unconsolidated, noncohesive soils and colluvial debris, including sands and gravels, rock fragments, weathered granitics, pumice and noncompacted glacial tills with low silt and clay content.
4. Precipitation Input	Expected 24-hr rainfall amount exceeds 4 in. at 5-yr recurrence interval.
B. Secondary Factors:	
1. Drainage Characteristics	Highly dissected (high density), closely-spaced incipient drainage depressions. Presence of bedrock or impervious material at shallow depth which restricts vertical water movement and concentrates subsurface flow. Presence of permeable zones above the restricting layer indicative of saturated flow parallel to the slope. Evidence of springs on the slope.
2. Bedding Structure	Extensive bedrock jointing and fracturing parallel to the slope. Bedding planes parallel to the slope (the stability influence of bedding planes horizontal or dipping into the slope is offset by extensive parallel jointing and fracturing).
3. Surface Slope Configuration	Smooth, continuous slopes unbroken by benches or rock outcrops. Intermittent steep channels occur frequently with lateral spacing of 500 ft or less. Perennial channels frequently deeply incised with steep walls of rock or colluvial debris. Numerous breaks in canopy due to blow-downs-frequent linear or tear-drop shaped even-aged stands beginning at small scarps or spoon-shaped depressions indicative of old debris avalanche-debris flow activity.

*Factors are quantified in Table 2.

Table 2. *Quantification of factors contained in the MMC.*

Factors*		Acronym
Primary Factors:		
Slope Gradient (degrees)		SLOPE
Soil Mantle Depth (m)		SOILDPTH
Surface Soil Texture		SURFTEX
(State Board of Forestry, 1981)		
Sands	10	
Loamy Sands	9	
Sandy Loams	8	
Fine Sandy Loams	7	
Loams	6	
Silt Loams	5	
Silty Clay Loams	4	
Clay Loams	3	
Clay	2	
Extra Fine Clays	1	
Five-yr, 24-hr storm (mm)		PRECIP5
Secondary Factors:		
Drainage Characteristics		
Density of incipient drainage depressions (number per 100 m across the slope)		INCIPIDD
Depth to resistant layer (cm)		DPTHREST
Soil texture above resistant layer (see SURFTEX)		DPTHATEX
Presence of springs (radial distance to nearest spring in m, maximum = 99 m, uphill coded +, downhill coded -)		SPRNGDST
Bedding Structure and Orientation		
Spacing of rock fractures (cm)		FRACSPAC
Bedding plane attitude (degrees perpendicular to slope)		BEDDATT
Surface Slope Configuration		
Outcrops on slope (number within 10-m radius)		SLOPCONF
Presence of slope break (within 10 m)		SLOPEBRK
Average spacing of intermittent channels (m)		SPACEINT
Contour radius of perennial channel (m)		CONTRAD
Channel material (percent stable, Pfankuch [1975])		CHANMAT
Presence of old slide features (distance to the nearest feature in m, maximum = 99 m)		DISTOSLD
Added Factors:		
Two-yr, 24-hr storm (mm)		PRECIP2
Distance to uphill slope break (m)		SLOPBRK2
Distance to stream (m)		DISST
Transformation = 1/SLOPBRK2 + l/DISST		SIMDIS

*Figures in parentheses are quantitative conversions for statistical testing and are not part of MMC (See Table 1).

was measured at each site with a clinometer. Soil texture (estimated by texture-by-feel) and depth were determined from exposed soil cross-sections at slide head scarps or hand-dug soil pits at control sites. Hydrologic factors, geology, channel conditions, and geomorphological factors were recorded from on-the-ground observations. If field conditions precluded measurement of secondary geomorphological variables, or if the observations were questionable, aerial photos were used.

RESULTS AND ANALYSES

Mass Movement Checklist

The MMC correctly classified 32 of the slide sites and 28 of the stable sites for an overall accuracy of 60 percent (Table 3). The pattern of classifications was, however, statistically significant at the 4 percent level based on a Chi-square test.

Different sets of quantitative thresholds for the four primary factors were tried to see if a higher

Table 3. *Observed and predicted conditions and accuracy of the MMC with different thresholds of slope and precipitation.*

Slope degree	Soil Depth cm	Soil Texture class	Precipitation mm	P*	Observed Condition	Predicted Condition Stable	Predicted Condition Slide	Correctly Classified percent
33	150	7	76	0.03	Stable	33	22	61
					Slide	17	28	
33	150	7	102	0.04	Stable	28	18	60
					Slide	22	32	
32	150	7	102	0.07	Stable	29	20	59
					Slide	21	30	

*Probability of a larger Chi-square test statistic under the null hypothesis that the classification occurs by chance.
Thresholds specified in the MMC

successful prediction rate would result from different threshold values (Table 3). A slightly higher success rate (61 percent) was achieved by lowering the precipitation threshold from >120 mm to >76 mm for the 5-yr, 24-hr storm. However, this slightly better differentiation resulted in the stable sites being more often misclassified as unstable. We found no other change in factor thresholds that resulted in a better differentiation.

Discriminant Analysis

We used linear discriminant analysis (Fisher, 1936) drawing on the same variables to see if it would be more successful than the MMC in classifying potential slide sites. A two group discriminant analysis is computationally equivalent to a multiple regression analysis with a dichotomous dependent variable. Using equations analogous to those for rotating axes in analytical geometry, an equation is computed for a line which provides the maximum separation between slide sites and nonslide sites when observations are projected onto it. Discriminant analysis has the desirable property that the value of the discriminant function for a particular site can be related to a probability that it will become a slide site if logged.

Discriminant analysis can be used only in those cases that have no missing values. The data for the two variables for bedding structure and orientation (FRACSPAC and BEDDATT, see Table 2 for acronyms) were not available for all 100 of the slide and control sites. Our sample size would have been 43 if both variables were included and could have been increased to only 73 if BEDDATT was deleted. Therefore, those two variables were deleted from the data set to maintain a larger sample size.

In the resulting discriminant function (Equation 1 in Table 4), Y is a discriminant score (canonical variate). If Y was positive, the site was classified as a slide; if Y was negative, the site was classified as a nonslide site. This equation correctly classified 42 of the 50 slide sites and 37 of the 50 control sites, for a total success rate of 79 percent.

Table 4. *Best discriminant functions.**

Discriminant Function	Observed Condition	Predicted Condition Stable	Predicted Condition Slide	Correctly Classified percent
Equation 1: Y = – 2.786 (constant) + 0.155(SLOPE) – 0.009(SPRNGDST) – 0.019(SLOPBRK2 – 0.006(DISST) + 0.130(INCIPIDD) – 0.211 (SURFTEX) + 0.011(CHANMAT) + 0.013(DPTHREST) – 0.003(SPACEINT) + 0.018(CONTRAD)	Stable Slide	37 8	13 42	79
Equation 2: Y = - 2.084 (constant) + 0.098(SLOPE) – 0.014(SPRNGDST) – 0.0025(SLOPBRK2)	Stable Slide	36 9	14 41	77

* See Table 2 for acronym definitions.

The "best" discriminant function (Equation 1 in Table 4) was determined using Mallows' Cp (Daniel and Wood, 1971) as a criterion for deciding which variables should be retained and which discarded. The function includes several variables which either must be obtained in the field (SURFTEX, DPTHREST, CHANMAT) or are difficult to measure on aerial photos (CONTRAD). We investigated alternative models to see how much classification accuracy would be lost by resorting to a simpler function. We eventually concluded that a three-variable (SLOPE, SPRNGDST, SLOPEBRK2) function presented the optimum practical balance between ease of use and accuracy of classification (Equation 2 in Table 4). This equation resulted in 41 of 50 slides and 36 of 50 control sites being correctly classified, giving a total correct classification of 77 percent. The significance of the discriminant function was tested using the F approximation to Wilks' Lambda (Wilks, 1932). Although the discriminant function was highly significant, such a test is not particularly relevant to its utility in identifying potential landslide sites. The classification accuracy is what matters. We used McNemar's test (Bishop et al., 1978) to compare the classification accuracies of the discriminant function with that of the MMC. Statistically, we estimate that Equation 2 will be superior to the MMC 26 percent of the time. The 95 percent confidence interval for that estimate is $\pm$14.5 percent.

While we believe that Equation 2 is, in fact, superior to the MMC considered by the Board of Forestry, it has not been subjected to as severe a test as has the MMC. When investigating the MMC, we were comparing its classifications to data not used in its development. When investigating the linear discriminant function, we were mode1 building. Equation 2 was fitted to the test data, and until it is tested with a new set of data there will be some doubt concerning its expected success in predicting slides and the degree to which its coefficients result from mathematical fitting and the degree to which they reflect underlying functional relationships. We have confidence in the linear discriminant function, however, because a similar function developed by Furbish (1981) was found to perform about as well on the test data as it did on the developmental data. Furbish's equation and one developed by Rice and Pillsbury (1982), were found to be over-fitted to the developmental data, and an equation with fewer variables performed as well (Furbish and Rice, 1983) or better (Rice et al., 1985) when used to classify test sets of data. The results from these two studies lead us to expect a similar robustness from Equation 2 and to prefer it over Equation 1.

DISCUSSION

Mass Movement Checklist

The poor differentiation between slide and nonslide sites obtained with the MMC in this study can be partially attributed to the low variability of several constituent variables in the test data. Only SLOPE usually differed much between slide and control sites. PRECIP5 was the same at both slide and control sites for most pairs of plots. Although our precipitation information came from maps, field measurements would not likely show appreciable differences between sites no more than a few hundred meters apart. Precipitation variables may be useful, however, in distinguishing the relative debris slide risk of more widely separated areas.

Our measurements of the soils variables (SOILDPTH, SURFTEX) have problems similar to PRECIP5 in that they don't often change abruptly over short distances if they support similar vegetation-a common situation since the MMC will be used in coniferous forests. In addition, depth tended to be correlated with slope in our data. Therefore, in a circumstance where slope is already a major discriminator of debris slide risk, information concerning soil depth adds little.

From our analyses we have concluded that the MMC, as constituted, cannot be expected to be an effective debris slide risk classifier in a small area such as an individual harvest unit. It may be effective at classifying broad areas, but even that hypothesis should be tested.

Linear Discriminant Function

Our linear discriminant analyses confirm our hypothesis concerning the efficacy of fine-scale geomorphic variables for identifying debris slide risk. Equation 2 (Table 4) addresses two factors promoting instability: the magnitude of the downslope component of the force of gravity (SLOPE), and the likelihood of excessive pore-water pressures to trigger a slide (SLOPEBRK2, SPRNGDST). It is clear why distance to a spring (SPRNGDST) might be inversely correlated with pore water pressures, but it is not obvious why distance to a slope break (SLOPEBRK2) should be indexing high pore water pressures. The prevalence of landslides just below slope breaks was noted first by Stiny (1931) and more recently by Furbish and Rice (1983). The authors in both investigations arrived at similar explanations for the phenomenon:

> Major slope breaks mark a discontinuity where material is nearer to failure-threshold conditions below the break than above. The regolith is thinner below the break because, due to steeper slopes, erosion can more nearly keep pace with weathering. Weathering of the parent material on the gentler slopes above the break will tend to cause strata to form parallel to the surface. These strata will conduct subsurface water to a point beneath the slope break. The thicker regolith above the slope break may be capable of delivering subsurface water to the slope break more rapidly than the thinner regolith below the break can transmit it to the stream. High pore-water pressures may result, causing debris avalanches. Farther down the slope, there is less likelihood of high pore-water pressures developing in this manner and, consequently, less likelihood of debris avalanches (Furbish and Rice, 1983: p. 258).

Equation 1 (Table 4) includes seven additional variables. Three (SURFTEX, DPTHREST, CHANMAT) are related to the properties of the soil material susceptible to failure, and the remaining four (DISST, INCIPIDD, SPACEINT, CONTRAD) are further elaborations on the geomorphic settings of slide and control sites. The latter set of variables serves to reiterate the usefulness of geomorphic descriptors in classifying landslide sites.

A landslide classification scheme based on a linear discriminant function would be superior to one based on a checklist even if both had the same expected classification accuracy. This is because a checklist only provides a yes or no answer to the question "Is the site under investigation a potential landslide site?" It provides no objective way of differentiating between extreme potential and modest potential for failure after logging. A linear discriminant function, on the other hand, can be used to estimate the probability of failure given a particular value of the canonical variable (Y). Since the probability of failure can be computed for any value of Y, the threshold of acceptable risk can be shifted to accommodate conflicting goals of forest utilization and environmental protection (Rice and Pillsbury, 1982). The overall accuracy will remain unchanged, but the distribution of errors can be shifted to greater or lesser protection of the environment with an accompanying lesser or greater utilization of forest resources.

CONCLUSIONS

Although the Mass Movement Checklist investigated here may be useful in distinguishing between generally stable and unstable environments throughout California, it is not much help in making on-the-ground decisions about the effects of logging individual sites. Using a linear discriminant function seems to be superior for evaluating the relative debris slide risk associated with logging a particular site.

Our results suggest that variables (mainly geomorphic), which can change markedly over short distances and which are surrogates for the forces affecting stability are most effective in evaluating the relative debris slide risk associated with logging.

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