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ON THE COVER: Development of Peninsular Ranges batholith, southern California and northern Baja California. **A,** Initial magmatic phase: emplacement of gabbro and differentiation of first andesitic magmas. **B,** Climactic phase of magmatization: andesitic volcanism on the surface, plutons of tonalitic to granitic composition rising as diapirs into overlying pile of volcanic debris. **C,** Generalized modern profile from Pacific coast inland to Sonora (ignoring Gulf of California). See article on p. 361 by R. Gordon Gastil.

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Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon

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ABSTRACT

The H. J. Andrews Experimental Forest can be divided into two zones of approximately equal area, each with strikingly different susceptibilities to erosion by rapid soil movements. A stable zone occurs at elevations above 900 to 1,000 m in terrain underlain by lava-flow bed rock. Since logging and road cutting began in 1950, only two small road-related slides have taken place in the stable zone. In contrast, the unstable zone, located at elevations below 1,000 m and underlain by altered volcaniclastic rock, has been the site of 139 slides during the same period.

Slide erosion from clear-cut areas in the unstable zone has totaled 6,030 m^3/km^2, or 2.8 times the level of activity in forested areas of the unstable zone. Along road rights-of-way, slide erosion has been 30 times greater than on forested sites in the unstable zone; however, only about 8 percent of a typical area of deforested land in the unstable zone is in road right-of-way. At comparable levels of development (8 percent roads, 92 percent clear-cut), road right-of-way and clear-cut areas contribute about equally to the total impact of management activity on erosion by landslides in the unstable zone. The combined management impacts in the unstable zone (assuming 8 percent road right-of-way and 92 percent clear-cut) appear to have increased slide activity on road and clear-cut sites by about 5 times relative to forested areas over a period of about 20 yr.

INTRODUCTION

In recent years the environmental impacts of forest management practices, especially clear-cut logging, have been the subject of heated, unresolved controversy in technical and popular literature and before legislative committees. Much of the concern has focused on the role of erosion as a mechanism of soil and nutrient export from the forest ecosystem and the possibility that accelerated erosion rates may result in decreased forest productivity. Increased erosion may also have negative impacts on water quality and stream and lake environments downstream from the site of timber harvest.

A major objective of the research program of the Coniferous Forest Biome (U.S./International Biological Program) is to develop a quantitative, holistic understanding of erosion processes in the productive timber lands of the Pacific Northwest. This paper is a progress report on one phase of the erosion studies—an evaluation of the occurrence of rapid mass-wasting events early in the management history of an experimental forest.

We have studied displacements of shallow soil masses in the H. J. Andrews Experimental Forest, where abundant background information on hydrology, geology, geomorphology, and history of land management activities is available. In all these respects, the forest is representative of much of the western Cascade terrane. Analysis of the slide history offers a measure of the impact of forest land management on mass-movement processes in this geologic-geomorphic terrane.

The inventoried mass movements are rapid, shallow (generally less than 5 m in depth) failures of more than 75 m^3 of soil-mantle material. The events include debris slides, slumps, rapid earthflows, debris avalanches, and debris flows, as defined by Varnes (1958). To simplify this discussion, we will refer to them collectively as slides.

Several lines of evidence suggest that shallow slides are dominant erosion processes in the western Cascade Range of Oregon. Fredriksen's (1970) work based on 13 yr of data on three experimental watersheds in the experimental forest indicates that the level of slide activity is a sensitive indicator of overall erosion rate. Further-

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more, slides may be the ultimate form of delivery of soil material to stream channels in situations where other processes, notably creep and deep-seated mass movement, have accomplished much of the downslope transport of soil material. Overland flow and surface erosion are generally assumed to be unimportant on undisturbed soils in the region (Rothacher and others, 1967). However, since soil mass movements expose bare mineral soil, accelerated surface erosion is a consequence of increased slide erosion.

STUDY SITE

The H. J. Andrews Experimental Forest is located at the eastern edge of the western Cascades, in the Willamette National Forest, about 80 km east of Eugene, Oregon. The forest boundaries surround a 6,100-ha watershed in which elevation ranges from 450 to 1,630 m and typical slopes vary between 10° and 36° (Dyrness, 1967). At elevations below about 1,350 m, Douglas fir and western hemlock are the dominant tree species; higher elevation timber stands are characterized by Pacific silver fir. Average annual precipitation totals approximately 240 cm and falls mainly between October and April.

Geology of the area may be divided into two units: predominantly altered volcaniclastic rocks at elevations below 900 to 1,000 m and, at higher elevations, unaltered lava flows. Much of the area above 900 m was glaciated during late Pleistocene time. The modern landscape in the volcaniclastic terrane bears abundant evidence of geologically recent slow, deep-seated earthflow and rapid shallow slides (Dyrness, 1967; Swanson and James, 1975).

METHODS

The history of slides in the Andrews forest has been compiled from (1) Dyrness's (1967) detailed study of mass movements resulting from storms in December 1964 and January 1965; (2) Fredriksen's (1965, 1970) extensive observations of experimental watersheds within the forest; (3) aerial photography taken in 1946, 1951, 1955, 1959, 1967, and 1972; (4) memos concerning storm impact in the early 1950s; (5) interviews with local U.S. Forest Service personnel; and (6) field observations. Field inspection included measuring height, width, and depth of slide scars with a range finder and noting bedrock geology, geomorphic setting, land use, and status of revegetation. The measurements of slide-scar geometry were used to calculate the volume of material moved. Time of each event was determined from sources (1) through (5) above and with dendrochronologic measurements of vegetation in and adjacent to slide scars.

Information on the history of logging and road construction in the forest was obtained from the Willamette National Forest timber-sale records and Timber Resource Inventory system. When the area of road right-of-way was not given, it was estimated from the measured road length and an assumed right-of-way width of 20 m.

RESULTS

Nearly 19 percent of the study area has been clear-cut, and 116 km of roads have been constructed since logging and road-cutting activities began in the forest in 1950. In the same period, more than 140 slides have occurred. Most of the slides took place in response to severe storms in January 1953, November 1953, December 1957, December 1964, January 1965, and November 1971. At least 3 slides were triggered by each of the storms, and 43 were reported for the December 1964 storm (Dyrness, 1967). During several of these storms, more than 30 cm of precipitation fell in 4 days (Fredriksen, 1965). Studies by Fredriksen (1965) suggest that this storm history is probably typical of the period of recorded observations dating back to the 1850s.

Definition of Stability Zone

The Andrews forest is underlain by geological units and associated soils that are distinctly different in their susceptibility to slides (Dyrness, 1967). Therefore, slide data will be analyzed for each area separately. Two landscape-stability units may be identified, an unstable zone in volcaniclastic terrane and a stable zone in the overlying lava-flow terrane. The contact between these two contrasting stability zones follows the bedrock contact at altitudes between 900 and 1,000 m (Swanson and James, 1975).

Altitudinal control of rates of snowmelt may reinforce the differences in landscape stability inherent in the two lithologic terranes. Many of the large storms that triggered slides involved rapid snowmelt in the low and middle elevations of the forest. This hydrologic factor may have contributed to the high levels of slide erosion in the unstable zone.

Analysis of the Slide Data

Land-management status and general slope-stability characteristics have important influence on the occurrence of slides (Table 1). More than 98 percent of the slides took place in the unstable zone, although it comprises less than half of the total area of the forest. Only two small, road-related slides occurred in the stable zone.

To assess the impact of timber management activities, we measured levels of slide occurrence in roaded and clear-cut areas relative to forested areas undisturbed by man. This was done by dividing the volume of material moved per square kilometre (Table 1) for roaded and clear-cut areas by the volume per square kilometre for forested land. As shown in Table 1 for the unstable zone, slides in clear-cut areas transported 6,130 m^3/km^2, which was 2.8 times greater than erosion by slides in forested areas. The difference between roaded and forested areas is even more striking. Slides in road rights-of-way moved 65,470 m^3/km^2 of soil material, or 30 times more than in forested areas.

A similar analysis for the stable zone is not possible because of insufficient data. The relative importance of roads and clear-cut areas, shown in Table 1 as the volume of material moved, is somewhat misleading because the road system is more nearly complete than in the first rotation of logging. Early timber sales in an area call for more road construction per unit area cut than later ones because the access is needed for fire protection and other management activities. At this time 25.6 percent of the unstable zone is clear-cut, which is 27.8 percent of the area eventually to be in clear-cut areas, assuming that an area completely managed for timber will be 8 percent road right-of-way and 92 percent clear-cut areas of various ages. Road right-of-way now covers 5 percent of the zone or 62.5 percent of the eventual coverage. Therefore, it is important to evaluate the effects of road cutting and logging so that both types of disturbance are con-

TABLE 1. SUMMARY OF DATA ON SLIDES IN THE H. J. ANDREWS EXPERIMENTAL FOREST, 1950-1974

Land status	Area (%)	Area (km^2)	No. of events	No./km^2	Volume material moved (m^3)	Volume material moved per km (m^3/km^2)	Slide erosion relative to forested area
Unstable zone (30.8 km^2)							
Forest	69.4	21.4	32	1.5	46,600	2,180	×1.0
Clear-cut	25.6	7.9	36	4.6	48,400	6,130	×2.8
Road right-of-way	5.0	1.5	71	47.3	98,200	65,470	×30.0
Stable zone (33.4 km^2)							
Forest	85.9	28.7	0	0	0	0	..
Clear-cut	12.3	4.1	0	0	0	0	..
Road right-of-way	1.8	0.6	2	3.3	420	700	..

sidered at comparable levels of development.

We can correct for this difference in road and cutting development by assessing slide erosion on a hypothetical square kilometre of the unstable zone. The data in Table 1 may be used in making this assessment if we assume that the hypothetical area has been entirely clear-cut logged and roaded progressively over the past 25 yr. Assuming that 8 percent of the area was in road right-of-way, there would have been 5,240 m^3 of erosion by road-related slides (8 percent of 65,470 m^3/km^2, from Table 1). The 92 percent area that was clear-cut logged would have undergone 5,640 m^3 of erosion by slide activity in the clear-cut area (92 percent of 6,130 m^3/km^2). By these calculations the clear-cut areas would have contributed slightly more than roads to the total erosion by slide activity from the managed site.

The sum of erosion from roads and clear-cuts totals 10,880 m^3 over the hypothetical square kilometre of the unstable zone. Assuming that the slide erosion in forested areas (2,180 m^3/km^2, from Table 1) represents the natural background level of slide erosion, management activities result in an increase by 5 times in slide erosion. However, as pointed out in the discussion below, there are several reasons why this assessment cannot be reliably projected to estimate impact of future management activities.

DISCUSSION

Analysis of data collected on the forest reveals an apparent increase in erosion by slides as a result of both logging and road construction. Deforestation of hillslopes results in a number of changes that may increase the probability of shallow failures of the soil mantle (see general reviews by Gray, 1970, and Swanston, 1970): (1) rooting strength is decreased, lowering the "apparent cohesion" of the soil (Swanston, 1970) and possibly releasing creep-generated stresses in the soil-root complex; (2) transpiration is decreased (Bethlahmy, 1962); and (3) snowmelt runoff may be increased (see, for example, Anderson, 1969; Rothacher and Glacebrook, 1968). These factors have been cited as contributing to a period of increased slide frequency after deforestation, especially between the time of decomposition of root systems of killed trees and establishment of stabilizing roots by incoming vegetation (Bishop and Stevens, 1964; Swanston, 1970; Nakano, 1971, and others). This temporal relationship between deforestation and slide activity has also been observed in the Andrews forest, where most hillslope failures in clear-cut areas occurred in the first 12 yr after cutting.

Since logging began in the unstable zone, the net result of deforestation has been an increase in slide erosion by a factor of 2.8. During the same period, no slides occurred in clear-cut areas in the stable zone. This indicates that on marginally stable sites, the stabilizing effect of vegetation is an important check on erosion but is of little consequence in more stable areas.

Many authors have observed that road construction is a more important factor than deforestation in accelerating erosion (Dyrness, 1967; Fredriksen, 1970; O'Loughlin, 1972, and others). Roads increase potential slope instability through all of the factors imposed by deforestation. However, they also create several additional critical problems: (1) interruption of surface drainage associated with road surfaces, ditches, and culverts (described by Dyrness, 1967); (2) alteration of subsurface water movement due to redistribution of soil and rock material, especially where road cuts intersect a water table (Parizek, 1971; Megahan, 1972); and (3) change in distribution of mass on a slope surface by cut-and-fill construction. As in the case of deforestation, maximum impact of roads probably occurs during the first few severe storms after disturbance. By 15 to 20 yr after construction, most unstable areas have undoubtedly failed. However, the 25-yr period of observation in this study is too short to reveal a clear attenuation of the impact of roads. In several cases in the forest, reconstruction of roads in problem areas appears to have contributed to failure during subsequent storms due to insufficient control of reconstruction work or inadequate correction of the original cause of failure.

Since road cutting began in 1950, the volume of slide material moved from road right-of-way in the unstable zone has been 65,470 m^3/km^2, which is 30 times the rate of slide activity in undisturbed forested areas and about 10 times that in clear-cut areas. The fact that only two small, road-related slides occurred in the stable zone underscores the contrasting effects of roads in the two terranes.

When road impact is assessed at a level of development comparable to timber cutting, roads contribute about half of the total management impact. The combined impact of roads and clear-cut logging has constituted a fivefold increase in landslide erosion relative to undisturbed forested areas.

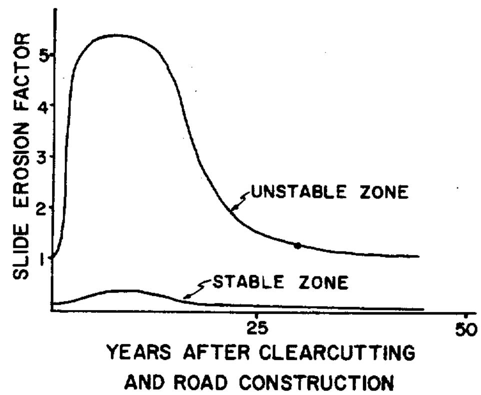

Figure 1. Relation of slide erosion ("slide erosion factor") to time since clear-cutting and road construction, based on the assumption that harvested forest land is 8 percent road right-of-way and 92 percent clear-cut. Slide erosion factor is a measure based on a unit that equals erosion by slide activity (in cubic metres per square kilometre) observed in forested areas of the unstable zone.

However, projection of these estimates to analyze impact of future management practices has several important limitations. For example, improved road design, placement and construction procedures, and innovative logging methods have been designed to reduce environmental impact. On the other hand, much of the least stable terrane in the forest has not yet been logged. If these sites are disturbed, the severity of impact will depend on the management procedures employed.

Analysis of slide history in the forest suggests that the impact of deforestation and road construction is reduced after 10 to 20 yr. Figure 1 shows a hypothetical relationship between the susceptibility of a roaded and clear-cut area to slide activity versus time since disturbance. The slide erosion factor is a running average of slide erosion spanning a number of years (storms of sufficient magnitude to trigger slides have occurred on the average of only every 4 to 5 yr). An erosion factor unit equals the level of landslide erosion (in metres per square kilometre) observed in forested areas. The erosion factor for the unstable zone is an estimate of the apparent increase in slide activity due to combined effects of road cutting and timber harvesting. As a result of the low level of erosional activity in the stable zone, the 25-yr available record does not provide sufficient data to quantify slide activity. Therefore, the curve for the stable zone shown in Figure 1 simply denotes a small but finite possibility of soil-mantle failure.

To evaluate how man's activities are modifying long-term erosion rates, it is necessary to take a temporal perspective even broader than the 50-yr time scale shown in Figure 1. Because erosion rates fluctuate in response to any severe disturbance of the vegetation, it is important to be able to compare the frequency and erosion impacts of disturbances under both management and premanagement conditions. However, there is not yet sufficient information to reliably contrast erosion rates under premanagement conditions of severe wildfire every several centuries with the projected erosional history of the same site over several timber management rotations.

There are two additional reasons why data in Table 1 do not completely reflect management impact on erosion rates. First, not all slide material directly reached stream channels; however, 85 percent of the slides, including all of the larger ones, transported most of the slide debris into or adjacent to streams. The second consideration is that many interrelated erosional processes are operating on the landscape. In the H. J. Andrews Experimental Forest, removal of dissolved solids, surface erosion, creep, and slow, deep-seated earthflow take place in conjunction with slides to transport soil material from hillslopes into stream channels and eventually out of the forest ecosystem. All of these processes are being monitored as part of several studies now underway in the forest. The ultimate objective of this research is to develop estimates of rates of erosion by each process and to determine how the rates are influenced by management activities.

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