EROSIONAL CONSEQUENCES OF TIMBER HARVESTING: AN APPRAISAL

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ABSTRACT. This paper summarizes our current understanding of the effects of timber harvesting on erosion. Rates of erosion on mountain watersheds vary widely but the relative importance of different types of erosion and the consequences of disturbances remain fairly consistent. Therefore these conclusions seem to be valid for most circumstances: Most of man's activities will increase erosion to some extent in forested watersheds; erosion rarely occurs uniformly; sediment production declines rapidly following disturbance; landslides and creep are the chief forms of natural erosion in mountainous regions; cutting of trees does not significantly increase erosion, but clearcutting on steep unstable slopes may lead to increased mass erosion; accelerated erosion is a possible undesirable side effect of use of fire in conjunction with logging; the road system built for timber harvesting far overshadows logging or fire as a cause of increased erosion; and potentially hazardous areas can be identified in advance of the timber harvest.
(KEY WORDS: lumbering; accelerated erosion; landslides; clearcutting; erosion control; roads; dry ravel; watershed disturbance; slash burning)

INTRODUCTION

Activities associated with timber harvesting constitute the most important human impact on forested watersheds. Because some level of increased erosion is an almost certain byproduct of logging, these activities have been of concern to forest managers for many years. Increased erosion is, however, only one of the consequences of logging. Timber harvest may alter water quality, affect site productivity, modify fish and wildlife habitat, change recreational opportunities, and alter the esthetic quality of the forest. In fact, it is mainly concern for esthetics and recreation, rather than any increased public awareness of the erosional effects of logging, that has focused so much current attention and controversy on forest management.

Until the late 1940's most timber was harvested on private lands in which the public felt it had little stake. Even on public lands timber harvest received little public scrutiny. Management was mainly concerned with the economical extraction of timber while insuring regeneration and minimizing erosion. Since the early 1960's this placid situation has altered drastically. Long accepted priorities are being challenged--partly due to increased leisure time, partly because of the urbanization of our population, and partly as a result of the growing concern about the quality of our environment. A substantial segment of the public seems more and more to view the National Forests, at least, as places to seek recreation and solitude rather than as producers of wood, forage, and water.

This paper considers the problem of erosion resulting from logging, with emphasis on conditions in the western United States. About 66 percent of the country's growing stock of sawtimber and about 81 percent of its softwood sawtimber are found in the West. And because most of the public controversy has centered upon the management of western forests, it seems logical to us that conditions there should be used to characterize the interrelationship between logging and erosion. This summary of our current understanding of the effect of logging on erosion builds upon earlier reports by Packer (1967a) and Dyrness (1967b). Besides including new information it differs from their works primarily in the importance which we attach to the effects of fire and landslides.

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EROSIONAL PROCESSES

Early erosion research in the United States centered on agricultural lands, where flowing water and wind are the primary transporting agents. Forested lands are often steep, and gravity is an important source of erosional energy. Agricultural soils, either naturally or as a result of cultivation, frequently have low infiltration rates, resulting in overland flow. Forest soils are normally highly permeable, and overland flow rarely occurs. Agricultural lands, either naturally or due to grading, frequently present plane surfaces which produce sheet erosion. Forest lands usually have uneven terrain that tends to concentrate quickly any flowing water into the channels. Furthermore, erosion is localized; it occurs mainly in gullies or as mass movements on steep terrain, removing mostly subsoil and parent material. Because of these differences, a given volume of soil eroded from forested land may represent a smaller degradation of the site than a similar volume from agricultural land, where raindrop splash, overland flow, wind erosion, and sheet erosion selectively strip away the more fertile upper layers of soil first.

Stabilizing a forested site after erosion does not depend upon the development of the pre-existing soil on that site. Because of species diversity in a forest, pioneers quickly invade most of the localized "sore spots," rapidly slowing down erosional processes which have started. Thus, recovery of the forest and of the watershed takes place in decades rather in the centuries which would be required to produce a mature soil. Fujiwara (1970), using tree ring data, estimated that 10 to 15 years were required for vegetation to cover a landslide area in Japan. He found that north and east facing slopes recovered almost twice as rapidly as dry south and west slopes.

Although forests often occupy steep lands, the cover of trees and understory is generally adequate to protect the soil. Erosion rates may vary considerably in relation to many site factors, but it is usually safe to assume that erosion from a well forested watershed represents a minimum for that site. The erosion rate reflects an equilibrium between the erosion and soil forming processes, as moderated by the vegetative cover on that site. The more important erosional processes operating on a watershed are sporadic; they are usually triggered by rare events, such as large storms, fires, or earthquakes, which temporarily disrupt the equilibrium. Records of erosion from natural watersheds are brief with respect to geological time. As a result, it is usually not clear whether the flush of sediment measured after a natural or man-caused disturbance will, with the passage of time, decline to the normal rate or continue at some above-normal rate.

Since most of the erosion rates available for analysis have been obtained on plots or experimental catchments it is difficult to interpret them. Bordered plots have a "belt of no erosion" (Horton, 1945) beneath their upper boundaries and therefore may underestimate erosion rates. Experimental catchments are commonly small upstream drainages with little opportunity for deposition of eroded material, such as might occur in the lower portions of a large drainage. On the other hand, some erosional features related to a well developed stream system can not be found in small headwaters drainages.

Characteristically, small experimental watersheds are given homogeneous treatments whale the surface of a large catchment would be very heterogeneous. For example, a large drainage under sustained yield management by clearcutting would have only 1 to 1.5 percent of its area harvested annually. Since previously cut areas would be revegetating, about 5 to 7 percent of such a drainage might be subject to accelerated erosion at any one time. After a large storm, Dyrness (1967c) found about 0.75 landslides per square kilometer in a 61-square-kilometer drainage containing 824 ha. of logging and 109 ha. of roads. This erosion represented a rate of about 5,000 metric tons per square kilometer -- a high rate, but only one-fifth of that measured in a 101-ha. experimental basin within the watershed which contained 24.7 ha. of recent patch cuts and 6.3 ha. of roads (Fredriksen, 1970). On the other hand, during the same event, in another small clearcut experimental catchment, Fredriksen (1970) found about one-thirtieth of the sedimentation estimated by Dyrness (1967c).

Besides problems of scale and heterogeneity, another difficulty is that researchers tend to be problem-oriented. As a result we find little data about landslides on terrain where they rarely occur or about fire effects where fire is not an important cause of accelerated erosion. This selectivity in research probably tends to bias available data in favor of high erosion rates.

To make the data cited here roughly comparable we have reported erosion in metric tons per square kilometer. However, the foregoing discussion should be kept in mind when comparing the standardized rates from different studies.

Amount of disturbance is usually equivalent to the area of bared soil. However, the presence of logging slash or residual understory vegetation may reduce the proportion of disturbed area which is actually bare. As a minimum, it is the area showing evidence of logging or road building. Mass erosion refers to the downslope movement of soil and parent material enmasse, usually during large infrequent storms. In many areas, such movement is the result of progressive failures (Terzaghi, 1962) the initial stages of which were the result of long-term gravitational creep of soil. In other areas, sudden release occurs as debris avalanches. Mass movements have been reported on slopes as gentle as 5 percent and as steep as 170 percent, although slopes of about 70 percent seem to be their most frequent site (Rice and Krammes [1971]). Geologic parent material plays an important role in occurrence of landslides. Dyrness (1967c) found 64 percent of the mass movements on a green breccia parent material occupying only 8 percent of the study area. Mass erosion is especially susceptible to triggering by disturbances, such as road building, logging, or 'vegetative manipulation.

Surface erosion is the movement of individual particles of soil. Other things being equal, the rate of this type of erosion is closely correlated with vegetative cover -- especially litter on the soil surface. Litter protects the soil surface from raindrop impact and promotes infiltration. Litter and the stems of vegetation also bar the downslope movement of surface soils, which might be started by gravity, flowing water, or animals. Accelerated surface erosion occurs when these barriers are destroyed by fire or logging or when the natural drainage pattern is disrupted by skid trails or roads.

WATERSHED DISTURBANCE

Many studies of the effect of timber harvest report the percent of area which has been disturbed. Although not as useful as erosion data, data on soil disturbance is presumed to be closely correlated. Certainly, bare and compacted soils resulting from logging disturbances are potential sites for erosion and surface runoff. However, because these areas are often not contiguous, eroded soil may come to rest on intervening undisturbed ground rather than move out of the watershed. The amount of soil disturbance from a timber harvest depends on the logging system, road network, slope, soil stability, volume of timber removed, and size of logs. Although generally undesirable from an erosional point of view, soil disturbance may be necessary for the regeneration of some species.

Watershed Disturbance from Roads

Most timber harvest will involve the construction of both permanent and temporary roads. Frequently, they cross steep topography of varying degrees of stability,

Table 1, Soil Disturbance from Roads

Logging System	Percent of logged area bared			Location	Reference
	Roads	Skid Roads and Landings	Total		
Jammer - - group selection	25-30	---	25-30	Idaho	Megahan and Kidd, 1972
High lead - - clearcut	6.2	3.6	9.8	Oregon	Silen and Gratkowski, 1953
Tractor - - selection	2.7	5.7	8.4	California	Rice, 1961
Tractor - - selection	2.2	6.8	9.0	Idaho	Haupt and Kidd, 1965
Tractor - - group selection	1.0	6.7	7.7	Idaho	Haupt and Kidd, 1965
Skyline - clearcut	2.0	---	2.0	Oregon	Binkley, 1965
Helicopter - - clearcut	1.2	---	1.2	---	([1])

[1]Estimated by Virgil W. Binkley, Pacific Northwest Region, U.S. Forest Serv., Portland, Ore.

where they often are a major source of erosion (Anderson, 1954). Most studies of erosion from logging roads have been made in problem areas and record large soil losses. On gentle, stable topography roads may cause little disturbance. For example, in the Bull Run watershed in Oregon, no increase in sedimentation was measured except for a brief period during road building. Thirty percent of the watershed was clearcut in patches requiring disturbance of 2 percent of the drainage by road construction. Watershed slopes averaged 8 percent and the soils were inherently stable. Consequently, in spite of an average rainfall rate of over 300 centimeters per year, the timber harvest had minimal adverse effects.

The amount of disturbance created by road construction depends upon its design standard, steepness of the slope, and total mileage of road -- which in turn is influenced by the logging system. For example, in steep topography in Idaho, high-lead logging in patch cuts, using a 213-meter yarding distance, disturbed less than 10 percent of the logging area; on the same 60 percent slopes, "jammer" logging roads spaced 60-120 meters apart disturbed 25 to 30 percent of the area (Table 1). Because of the excessive disturbance associated with "jammer" logging it is becoming less used.

Skyline, balloon, and helicopter systems are being developed to permit the logging of steep topography with a minimum amount of road disturbances. Analyzing a 1,600-hectare drainage, Binkley (1965) estimated that skyline yarding would save from 2.2 to 2.9 kilometers of road per square kilometer over that required for high lead. About 700,000 hectares in Washington and Oregon are suitable for single span skyline operations (U. S. Forest Service., 1970). On more gentle topography, tractor logging requires few haul roads but more skid trails. However, even in these areas, haul roads are still found to be a major source of sediment (Rice, 1961; Haupt and Kidd, 1965).

Watershed Disturbance from Yarding

Although the severe disturbance caused by road construction is the most important source of sediment, the process of cutting and moving logs to a landing frequently disturbs more area (Table 1). Amount of yarding disturbance, as with roads, depends upon slope, volume yarded, size of logs, and logging system (Table 2). Some recently developed cable systems cause significantly less soil disturbance than conventional systems.

The significance of bare or compacted soil as a source of erosion depends upon weather and soil characteristics. Single-grained soils, such as those developed from pumice and granodiorite, often are seriously eroded when bared. In contrast, finer textured soils, such as may develop from basalt and sedimentary rock, are especially susceptible to puddling, compaction, and subsequent rilling. Heavy loam soils are usually the most resistant to erosion.

Table 2, Soil Disturbance from Logging

Logging System	Percent Bare Soil	Location	Reference
Tractor - clearcut	29.4	E. Washington	Wooldridge, 1960
Tractor - clearcut	26.1	W. Washington	Steinbrenner and Gessel, 1955
Cable - selection	20.9	E. Wash. and Ore.	Garrison and Runnel, 1951
Tractor - selection	15.5	E. Wash. and Ore.	Garrison and Runnel, 1951
High lead - clearcut	14.1	W. Oregon	Dyrness, 1965
High lead - clearcut	12.1	W. Oregon	Ruth, 1967
Skyline - clearcut	12.1	W. Oregon	Dyrness, 1965
Skyline - clearcut	11.1	E. Washington	Wooldridge, 1960
Skyline - clearcut	6.4	W. Oregon	Ruth, 1967
Balloon - clearcut	6.0	W. Oregon	Dyrness[1]

[1]Dyrness, C.T. (Unpublished data on file, Pacific Northwest Forest and Range Exp. Sta., Corvallis, Ore.)

SURFACE EROSION

Surface soil erosion is less critical on steep forest lands than erosion from mass soil movements. It is the form of erosion most closely related to watershed disturbance -- whether natural or man caused. It results primarily from the exposure of mineral soil by yarding operations, fire, and by the disruption of natural drainage patterns by skid trails and road construction.

Surface Erosion from Roads

Sediment production measured at the mouths of watersheds after road construction is highly variable. It has ranged from no detectable change on glaciated lands

Table 3, Erosion and Sedimentation from Logging Roads

Location	Soil parent material	Slope	Type of vegetation	Type of study	Years sampled	Average amount of£ material removed for the period: Undisturbed	Disturbed	Ratio disturbed undisturbed	Reference
		Pct.			No.	Metric tons/sq. km./yr.			
Idaho	Granite	70	Ponderosa Pine	Deposition in dams in small ephemeral drainages	6	8.8	396	45.2	Megahan and Kidd, 1972
Oregon	Sandstone	20-50	Douglas-fir	Suspended sediment from watersheds	1	Approx. 42	94	2.2	Brown and Krygier, 1971
Colorado	Glaciated Metamorphic	30-40	Lodgepole Pine Subalpine Fir	Deposition in dams in perennial drainages	10-14	1/2.2	(2/)	0	Leaf, 1966
Idaho	Granite	35-55	Ponderosa Pine	Deposition in sediment dams in ephemeral and perennial streams	4-5	0.0	1.2	--	Haupt and Kidd, 1965
Oregon	Glaciated basalts	20-30	Douglas-fir	Suspended sediment at gaging station	4	Average 10 ppm	(3/)	--	(4/)
Oregon	Tuffs and breccias	55	Douglas-fir	Suspended sediment and bedloads from watersheds	2	25.6	56	2.2	Fredriksen, 1970

1/ Assumed sediment volume weight of 70 pounds per cubic foot.
2/ Slight increases traced to roads but not significant
3/ No changes except slight increase during road construction.
4/ Unpublished data, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon

with gentle slopes in Oregon and Colorado to an average increase of 45 times for a 6-year period on steep, highly erodible land on the Idaho batholith (Table 3).

As in many types of erosion, the rates measured immediately after road construction decrease rapidly. The time required to approximate normal varies considerably, depending on regional differences. In Idaho, the initial sedimentation rate for the first 7 months after construction of roads in Deep Creek averaged 2,912 metric tons per square kilometer per year. The rate declined rapidly to about 107 tons per square kilometer 6 years after construction. This rate was, however, still about 12 times greater than that expected from undisturbed watersheds. In western Oregon, suspended sediment from eroded watersheds was 1,850 ppm as a result of the first storm after logging and road construction (Fredriksen, 1970). After this initial flush of sediment 250 times greater than normal, the concentration decreased to nine times normal after 9 weeks, and to 2½ times normal after the end of 2 years. Subsequent storms again increased sedimentation greatly. Similar decreases in sediment production have been reported by Haupt and Kidd (1965) in Idaho, by Brown and Krygier (1971) in Oregon, and by Reinhart, et al. (1963) in West Virginia.

Surface Erosion from Logging

Compared to road construction the logging operation usually results in minor erosion if yarding is done with care. Most often, however, studies fail to clearly distinguish erosion resulting from logging, from that attributable to road construction or, in some cases, from slash disposal by fire. A few studies have used plots to measure directly erosion resulting from logging, but most give indirect evidence in terms of sediment measured in streams or sediment basins.

Of those studies separating erosion into its various causes, several have reported that any changes in sedimentation resulting from logging alone were not significant (Meehan et al., 1969; Lull and Satterlund, 1963; Packer, 1967a; Brown and Krygier, 1971). Fredriksen (1970) could detect no rise in sedimentation rate from a watershed in which 30 percent of the area was clearcut and high-lead logged. But the effect of logging may have been obscured by erosion from previously built roads. We consider it unlikely, however, since an adjacent unroaded logged area produced no noticeable change in sediment until several large landslides occurred as a result of a major storm.

Bethlahmy (1967) used plots to measure the effect of logging and aspect on soil movement in the southern part of the Idaho batholith. Logging increased sediment movement by fourfold on plots on southwest slopes with 42 percent bare soil. On northwest slopes with 3 percent bare, sediment increased fivefold, but the total amount was only 5 percent of that on the southwest slopes. In the same area, logging sandy soils on steep slopes increased sedimentation by about 60 percent (Megahan and Kidd, 1972).

These findings suggest that surface erosion resulting from the logging operation itself is not serious. In most operations, most of the area remains essentially undisturbed. Even logging systems that cause the most disturbance seldom bare more than 30 percent of the soil surface (Table 2). Since surface erosion depends primarily on extent and continuity of bare areas, soil loss is usually slight. Surface erosion that does occur frequently comes from localized disturbed areas (Rice and Wallis, 1962; Megahan and Kidd, 1972).

Surface Erosion Effects of Fire

Fire is often used to dispose of logging debris and to prepare a suitable seedbed. Dyrness (1965) summarized its effects on the erosion potential of forested watersheds. Few studies, however, relate erosion specifically to the burning of logging slash. Research in southern California, where post-fire erosion is an important management problem, has produced most of the data on fire effects. Consequently, some of our conclusions necessarily rely on analogy to the effects of wildfires in chaparral. However, observations leave little doubt that accelerated erosion is a common result of fire on forest lands. The most obvious effect of fire is the removal of ground litter. In slash disposal fires, by regulating burning, it is possible to control the amount of litter consumed and, presumably, the resulting erosion. Paul E. Packer reported (unpublished data) that broadcast burning of slash in a clearcut block in western Montana reduced ground cover by at least 50 percent. But the resulting increase in erosion was less than 3.5 tons per square kilometer the first 2 years after burning. On the other hand, Rich (1962) estimated erosion of about 5,250 metric tons per square kilometer from one intense storm which struck a logged area in Arizona which subsequently burned in a wildfire. In wildfires, litter and other fuels are so dry that almost all fine organic matter is consumed, leaving virtually the entire soil surface exposed to erosion.

Slash fires may lead to erosion by dry ravel on steep (greater than 60 percent) slopes. R. C. Mersereau and C. T. Dyrness reported (unpublished data) that on the H. J. Andrews Experimental Forest, small bare plots on a burned clearcut yielded ravel material at a rate of from 66.5 to 1,050 tons of soil per square kilometer between the ninth and fourteenth month after burning. Earlier records from one plot suggested to them that this volume represented no more than 40 percent of the total erosion since burning. For the whole watershed, 27 percent of which contributed little or no sediment, the rate averaged 469 tons per square kilometer. Almost three quarters of this originated from talus slopes that made up less than 15 percent of the watershed. Because of rapid revegetation, ravelling during the second year after burning was slight.

Krammes (1965) measured increases in dry ravel of from four-to sixteenfold after a brush fire in southern California. Rates ranged from 143 to 4,912 tons per square kilometer during the first year. The rate depended, primarily, upon whether or not measuring sites were on steep slopes adjacent to rejuvenated stream channels.

Increased overland flow as the result of fire is often the explanation for increases in erosion. The probable mechanism by which fire decreases infiltration thereby increasing overland flow has been studied in southern California (DeBano and Krammes, 1966). Heat from the fire creates a water repellent barrier in the soil. The severity of this condition is positively correlated with burning temperatures (DeBano, 1969b). Water repellency is more severe in coarse textured soils than in fine textured soils (DeBano, Mann, and Hamilton, 1970).

Soil water repellency is a potential erosion problem on most forest lands. It has been observed under a variety of forest conditions both in unburned areas (DeBano, 1969a; Meeuwig, 1969) and after fire (DeBano, 1969b; and unpublished data by L. F. DeBano and R. M. Rice).

Besides directly causing erosion, water repellency may accelerate it indirectly by retarding vegetative recovery. Osborn (1969) found that a water repellent soil reduced germination of ryegrass to zero in pots tipped to a 30^0 slope. Plots which had been treated with a wetting agent to overcome soil repellency produced four times as much vegetation as the untreated controls (Osborn, et al., 1964). The water repellent barrier can reduce the depth of soil through which the water moves to as little as 2 to 5 centimeters. The result is increased overland flow and erosion.

Erosional effects of fire, as with other disturbances, decline rapidly. Paul E. Packer found (unpublished data) that most of the effects detrimental to watershed performance were temporary and that surface erosion returned to normal by the third year after slash burning. Fredriksen (1970) reported that understory vegetation on two logged and burned areas in Oregon had returned to near normal in 1 to 4 years. Recovery is usually more rapid in well watered areas. Brown and Krygier (1971) reported that: a 100 percent clearcut and burned watershed, which had a five-fold increase in sedimentation was revegetating at a rate that could be expected to return sediment yield about to normal in the fifth or sixth year after burning. A 10-year recovery is considered normal in southern California following brush fire (Rowe, Countryman, and Storey, 1954). However, some effects linger on. Anderson and Trobitz (1949) estimated that sediment in major flood in southern California was about 16 percent above normal 15 years after a 60 percent burn on a watershed.

MASS SOIL EROSION

Mass failures are a natural slope-sculpturing process which are a function of climate, topography, soils, and geology. Mass failures occur when the internal strength of a soil is exceeded by gravitational and other stresses. While man's activities can alter the strength or the stresses on the slope it is misleading to think of them as the sole cause of mass failures; to quote Sowers and Sowers (1951):

> In most cases, a number of causes (for landslides or flows) exist simultaneously, and so attempting to decide which one finally produced failure is not only difficult but also incorrect. Often the final factor is nothing more than a trigger that set in motion an earth mass that was already on the verge of failure.

Mass Erosion from Roads

Roads undercut upslope soils and may alter the natural drainage from a hillside. By exposing formerly buried material to weathering they may also change the strength of the slope. Road fills place additional weight on the underlying soil mass. The fills themselves are frequently over-steepened slopes of reduced strength and are prone to failure. Consequently, it is not surprising that roads are frequently associated with landslides. During the 1964-1965 floods, 72 percent of the landslides on the entire H. J. Andrews Experimental Forest were associated with roads (Dyrness, 1967c) -- although roads occupied only 1.8 percent of the area. A reconnaissance of damage resulting from this same storm on the National Forests of Washington and Oregon found "roads were involved in 60 percent of all major storm damage reports. Mass soil movements were listed as a primary cause of damage" (Rothacher and Glazebrook, 1968). In southern Idaho, Jensen and Cole (unpubl.) found 89 mass failures as a result of the same storm, near the Zena Creek logging study; 90 percent of them were associated with roads. They also reported that mass failures occurred on other roads in the area which had been stable for about 10 years since construction. A single road slide in the Deer Creek watershed in western Oregon produced 317 metric tons of sediment; 40 percent of the total sediment yield for the year (Brown and Krygier, 1971). The 303-hectare drainage contained 4 kilometers of roads constructed to permit clearcut logging of about 25 percent of the watershed.

In all these cases roads had been constructed on steep mountainous topography and were subjected to severe storms. On unstable geological formations, roads can trigger mass movements even on less steep topography.

Mass Erosion from Logging

Part of a soil mass's strength is due to the anchoring effect of tree roots. Therefore, it seems reasonable that the susceptibility to landslides would gradually increase as these roots decay after logging. This phenomenon has, in fact, been reported. For example, about 5 years after clearcut logging on 67-percent slopes in coastal Alaska, Bishop and Stevens (1964) found that both the number and acreage of landslides increased by at least fourfold. Later, Swanston (1969) reported that evidence of root decay became visible between 4 and 5 years after logging. Fujiwara (1970) studied aerial photographs of two forest areas in Japan. He found a slight increase in landslides in clearcut areas 3 years after cutting and about a tenfold increase 5 to 8 years after cutting. He also attributed this difference to the loss of the stabilizing effects of roots.

Croft and Adams (1950), while studying landslides in timbered areas of the Wasatch Mountains of Utah, attributed the greater frequency of landslides in second-growth timber largely to the loss of mechanical support provided by the more extensive root system of the former old growth stand. Similar conclusions have been reported elsewhere; for example, in Italy, by Cappuccini and Bernardini (1957); in Alaska, by Bishop and Stevens (1964); in Japan, by Kawaguchi, et al. (1959); and in Czechoslovakia, by Zaruba and Mencl (1969).

The importance of logging as a cause of mass soil movement is shown by an aerial photographic study of two adjacent 117-sq. km-drainages in western Oregon (USDA Forest Service, 1966). The flood of 1964-1965 had triggered numerous landslides. The control drainage, virtually undisturbed by logging, showed evidence of 27 mass movements, three of which were along the only road within the drainage. The other drainage, actively logged for several years, showed evidence of 55 mass movements. Among the 55 mass movements, three were not connected to roads or logging, 40 were in some way connected to roads, and 12 were connected to logging.

Rothacher and Glazebrook (1968), reporting the effects of the same 1964-1965 storm, found the greatest evidence of increased instability after logging, which was not associated with roads, on the granitic soils of southwest Oregon. Numerous small debris avalanches were found in logged areas, but none was observed under undisturbed timber. In all cases slopes were steep, usually exceeding 60 percent. In other analyses of the same storm, Fredriksen (1970) and Dyrness (1967c) found that clearcutting apparently increased the number of landslides, but roads had an even greater influence. Dyrness counted about 0.2 landslides per square kilometer in undisturbed areas, 2 per square kilometer in logged areas, and 76 per square kilometer in areas disturbed by roads; 83 percent of the landslides were on slopes exceeding 45 percent. Thus, it appears that while logging can trigger landslides on potentially unstable soils, roads are more often the trigger.

Mass Erosion Effects of Fire

Since one of the principal effects of fire is reduced infiltration, it seems reasonable that a recently burned area would be less susceptible to landslides than a fully vegetated area. Reduced infiltration makes it difficult to achieve the high levels of soil water associated with mass movements. Circumstantial evidence from brushfields in southern California supports this assumption. Landslides in two similar drainages were carefully mapped from a helicopter shortly after an intense storm in 1969. One drainage had burned the previous summer. The other had not burned for 50 years. G. T. Foggin estimated (unpublished data) that landslide erosion in the unburned drainage was 1,800 metric tons per square kilometer; and 1,100 tons per square kilometer in the recently burned drainage. The effect of decaying roots is suggested by measurements on the nearby San Dimas Experimental Forest, which had burned 9 years earlier. There, landslides eroded similar slopes and soils, at a rate of 33,400 metric tons per square kilometer (Rice and Foggin, 1971). These data suggest that while there may be some temporary lessening of landslide hazard after a fire, this benefit is short-lived. After that, while a forest is recovering, a period of maximum hazard will be encountered wherein the susceptibility of landslides is much worse than it is immediately after fire or with a full vegetative cover.

REDUCTION OF EROSION AND SEDIMENTATION

Some increase in erosion is probably an unavoidable adjunct to timber harvest. However, erosion can be reduced if the hazards are appraised in advance of disturbance. Appropriate strategies can be worked out to avoid or minimize most erosion hazards. A large body of knowledge is available to aid in selecting strategies; however, costs of erosion control tend to increase geometrically as the acceptable erosion rate decreases.

Some guides (e. g., Kidd 1963), relate to erosion control during logging, but most, recognizing the relative seriousness of the hazards, deal primarily with the control of erosion from roads. Roads occupy a small portion of the timber harvest area, are readily accessible, and yet constitute a major source of erosion. Consequently, fairly intensive erosion control measures on roads are possible and economically justifiable. A straw mulch and grass seeding on road-cut slopes in Oregon (Dyrness, 1970) reduced surface erosion by 88 percent. Revegetation did not, however, prevent small mass failures of backslopes and fills. Two studies on steep road fills in Idaho indicate reductions of 98 and 99 percent from the use of straw mulch plus a net covering to hold the mulch in place (Bethlahmy and Kidd, 1966). Kidd and Haupt (1968) provide guides for revegetation of abandoned road beds. Haupt (1959) showed the value of buffer strips below roads for the purpose of intercepting the eroded material destined for a stream channel. Packer (1967b) and Packer and Christensen (1964) provide guides for reducing road erosion and preventing sediment movement into streams.

Since roads permanently alter the terrain, the careful design of new roads can greatly minimize the erosional impact of the timber harvest which they serve. Routes can be chosen to avoid steep or unstable terrain to the greatest degree possible. Variation of standards for alignment and grade can cause the road to more nearly conform to the terrain thereby reducing erosion. The materials and methods used in the construction of a road can be chosen to minimize its initial impact and subsequent erosion.

Land stratification is one possibility for reducing landslides being triggered by logging or road construction. Such stratification has been accomplished on some National Forests. For example, Bailey (1971) found that 16.2 percent of the Teton National Forest was highly unstable and unsuitable for logging, road construction, or other soil disturbance. Another 41.2 percent of the forest was of questionable stability which could be used if managed cautiously. The remaining 42.6 percent was considered stable under present conditions.

Delineation of strata is based on some or all of the following criteria: geology, landform, soils, climate, slope, and vegetation. The efficacy of stratification was shown in the Santa Ynez drainage of southern California. E. Kojan, G. T. Foggin, and R. M. Rice found (unpublished data) that 80 percent of the landslides occurring in a large storm in 1969 were on the 20 percent of the study area which had previously been typed as unstable (primarily on the basis of landform) on aerial photos.

The choice of a logging system has a significant impact on the amount and type of erosion which may accompany a timber harvest (Table 1,2). Consequently, the erosional effects of a timber harvest can be greatly reduced by using a logging system which will minimize the erosional "costs" of a particular timber harvest. Skyline, balloon, or helicopter systems are especially effecttive for reducing logging impacts.

CONCLUSIONS

Erosion rates in forested mountain watersheds are highly variable -- depending upon differences in slope, soils, geology, vegetation, and climate. Because of this natural variability and the scarcity of appropriate data, it is difficult to estimate quantitatively the erosion hazard posed by any particular timber harvest. Nonetheless, the relative importance of different types of erosion and the consequences of various disturbances remain fairly consistent. Therefore, it is possible for us to draw these conclusions which we consider valid in most circumstances:

- Erosion in an undisturbed forest represents a minimum for the site, and most of man's activities will increase the erosion rate to some extent. The environmental objective of a timber harvest, therefore, is to minimize the erosional "costs" and to balance them, together with other resource "costs," against the wood products benefits received from the harvest.

- Erosion rarely occurs uniformly in a forested watershed. Even in a logged area, most of the soil surface is undisturbed. Because erosion tends to be localized, it is often deep and includes a large proportion of subsoil and weathered parent material. The volumes of sediment lost from the site, consequently, probably represent much less actual degradation of site quality than would be the case if erosion were taking place more or less uniformly over the whole surface.

- Because of the diversity of species within a natural forest ecosystem, bared areas are quickly invaded by pioneer species, and initially high rates of sediment production decline rapidly. Erosional recovery does not require the return to predisturbance conditions but rather to the cessation of accelerated erosion, which occurs much sooner.

- Landslides and creep are the principal forms of natural erosion in mountainous regions under a wide variety of climates and site conditions.

- The cutting of trees, by itself, does not significantly increase erosion, but clearcutting on steep unstable slopes may lead to increased mass erosion. Therefore, on steep slopes, slope stability requirements as well as silvical considerations should weigh heavily in the selection of silvicultural systems.

- Accelerated erosion is a possible undesirable side effect of use of fire following a timber harvest. The effects of fire are most harmful on steep slopes, where it induces dry ravelling, and on coarse-textured soils, where it can -- by the creation of a water repellent layer -- increase overland flow and retard the regrowth of the forest.

- The road system installed to facilitate timber harvest far overshadows logging or fire as a cause of accelerated erosion. Roads increase surface erosion by baring soil and concentrating runoff. And they trigger landslides more frequently than any other disturbances by man.

- Most erosion tends to occur in localized unstable areas. Consequently, it is possible, particularly with respect to landslides, to identify potentially hazardous areas in advance of the timber harvest. Erosion associated with timber harvest can be substantially reduced by either avoiding these areas or by minimizing the effects of disturbance.

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