

Chapter 5

Erosional Processes and Long-Term Site Productivity

Frederick J. Swanson, James L. Clayton, Walter F. Megahan, and George Bush

ABSTRACT

Both natural and management-imposed disturbances of forest ecosystems lead to accelerated soil erosion. However, the areal extent, degree, and duration of management-accelerated erosion vary among erosion processes. Some studies report dramatic increases in surface and debris-slide erosion for periods of a year to a decade or more following clearcutting and slash burning. However, the long-term (multirotational) consequences of these periods of accelerated erosion are unknown at present. In a few situations in the Pacific Northwest, erosion alone appears to have been the primary cause of pronounced, extensive (10+ ha), and prolonged (rotation time scale) reduction of site productivity. More commonly, where severe disturbance has diminished site productivity, erosion acts in combination with other factors, such as loss of nutrients, soil biota such as mycorrhizae, and soil organic matter. Loss of biological integrity of a site leads to loss of physical stability, and the resulting erosion may prolong the period of recovery.

INTRODUCTION

Soil erosion affects long-term site productivity in several ways in the steep, unstable forest land of the Pacific Northwest. Here, we discuss soil erosion—the detachment, transport, and deposition of particles—and distinguish it from soil disturbance (treated in chapter 4)—the modification of soil properties, by processes such as compaction, while soil is in place. Various soil-erosion processes (defined in Table 5.1) can influence site productivity by removing soil and propagules and by disrupting tree growth chronically (frequently, relative to the age of the vegetation) or episodically. Where erosion removes soil from potential tree-growing sites, nutrients and growing medium are lost. This loss can be very serious in mountainous areas because the entire soil mantle may be stripped away, exposing bedrock or infertile subsoil. Where surface erosion and freeze-thaw processes remove propagules such as seedlings or seeds, reestablishment of desired species may be delayed or even prevented. Where chronic soil movement such as large, slow-moving landslides disrupts tree growth by tipping and splitting boles and shearing roots, quantity and quality of forest products are degraded. Unfortunately, few of the effects of any of these processes on site productivity have been assessed. In response to public pressure through legislation and litigation, erosion research in Pacific Northwest forest lands has centered mainly on effects on water quality and fish habitat.

In this chapter, we summarize the relations between erosion processes and site productivity by considering general perspectives on soil loss, the character of forest soils from an erosion viewpoint, the erosion regime in the natural system and in managed forests, and some possible long-term impacts. Time scales of interest range from the short term—for instance, the response time of a forest-soil system to a single disturbance such as wildfire or timber harvest—to the much longer term—for instance, a set of responses, over a thousand years or more, to multiple disturbances such as wildfire or timber harvest. The multiple-disturbance framework is relevant because this is the time scale over which the soil has formed.

DETERMINING SOIL-LOSS TOLERANCE

Many of our perspectives on soil loss come from nonforested agricultural lands. Since 1950, world food output has more than doubled, but this gain has often been achieved by adopting agricultural practices that lead to excessive erosion. Brown (1981) estimates that at least one-fifth, and perhaps as much as one-third, of the world's cropland is eroding at rates sufficiently high to result in long-term declines in productivity. Concern

TABLE 5.1. Definitions of soil erosion processes.

<i>Term</i>	<i>Definition</i>
Creep	Very slow (mm/yr) downslope movement of the soil mantle resulting from deformation of soil under the influence of gravity.
Debris flow	Very fast (m/sec) movement of water-charged soil, alluvium, and vegetation down stream channels.
Debris slide	Very fast movement down hillslopes of soil under the influence of gravity. Commonly containing high concentration of water. Initial sliding surface generally 1–4 m below ground surface.
Earthflow	Slow (cm to m/yr) downslope movement of earth material under the influence of gravity. Moving mass generally 3–20 m thick. Sliding surface is much thinner, and may be planar to irregular in form.
Gully erosion	Removal of soil by running water and development of channels greater than about 0.1 m ² in cross-sectional area.
Mass movement	Downslope movement of a mass of earth under the influence of gravity. Includes creep, debris flow, debris slide, slump, and earthflow.
Overland flow erosion	Soil movement resulting from unchanneled flow of water in a thin film over the ground surface.
Raindrop splash erosion	Detachment and transport of soil particles resulting from the impact of rain or throughfall drops.
Ravel	Downslope particle-by-particle movement of soil on steep slopes resulting from soil detachment by wetting-drying, freezing-thawing, animal activity, or other processes not involving precipitation and overflow.
Rill erosion	Soil movement by channelized flow of surface water as it erodes rills (small channels less than about 0.1 m ² in cross-sectional area).
Slump	Slow to fast (m/hr to cm/yr) rotational mass movement along concave sliding surface.
Surface erosion	Particle-by-particle movement of soil over the ground surface as a result of gravity or flowing water. Includes ravel, raindrop splash, and overland flow erosion.

about erosion of croplands has led to the concept of soil-loss tolerance (T values), defined as the maximum rate of annual soil erosion that will permit high crop productivity to be sustained economically and indefinitely (Wischmeier and Smith 1978).

Soils vary in their ability to withstand losses from erosion. T values on croplands commonly range from 1 to 10 Mg/ha, depending on soil depth and thickness of the A horizon (uppermost zone of the soil profile where organic matter has accumulated and soluble salts have been leached). T values on forested lands have not been established, principally because of the difficulty in isolating the magnitude of productivity declines accompanying soil loss. Establishing this link in forest stands is greatly complicated by large variation in erosion rates over small areas, variability in annual precipitation (no irrigation), length of growth cycle from planting to harvest and the changing dynamics of crop growth over this cycle, variable effects of diseases, pests, and fertility levels, and differences in dominant erosion processes between steep forest terrain and relatively flat agricultural fields.

Determining soil-loss tolerance also requires estimating the rate of soil formation (pedogenesis) to offset erosion losses. Most cropland soils are formed on relatively deep, unconsolidated alluvium (deposits of stream-transported sediment) or colluvium (deposits of material transported by gravitational processes), and soil-formation rates are dictated by pedogenic processes such as accretion of organic matter, transport of dissolved bases, and redistribution of free silica, sesquioxides, and clays. Large areas of Northwest forest land are located on montane sites (Coast Range, Cascade Range, Northern Rocky Mountains) marked by poorly developed soils formed over consolidated bedrock. Although the same pedogenic processes are at work, rates of soil formation are more often limited by the rates of advance of the bedrock weathering front, soil mixing, and erosion processes characteristic of steep forested slopes. McCormack et al. (1982) suggest that soil-forming processes are much slower on mountain slopes than in unconsolidated alluvium. To arrive at estimates of soil-formation rates on upland slopes, we rely on watershed studies of chemical and erosional denudation, by measuring the amount of weathered material removed in solution and sediment transport. This approach assumes that soil depth averaged over an undisturbed watershed is in a state of quasi-equilibrium, so the weathering front advances at a rate equal to that of the denudation loss (Clayton and Megahan 1986). This is probably a reasonable assumption on the time scales of centuries to a few millennia for mountain areas of the Pacific Northwest.

Calculating T values for forest land is further complicated because the land-use systems and physical

environment of forestry in the western United States differ from those of agricultural lands in several important respects. First, the forest crop is harvested much less frequently than agricultural crops. Second, forestry disturbs the land in different ways and to differing degrees than agriculture, generally involving less intensive individual site treatment, but requiring road construction. Finally, erosion in steep landscapes is unlikely to be uniform in space, concentrated on localized sites and commonly involving considerable deposition downslope, or in time, dominated by landslides which occur infrequently.

THE FOREST SOIL RESOURCE

As the rooting medium for higher plants, soils provide four essentials: water, most nutrients, structural support, and soil biota. First, according to the National Soil Erosion-Soil Productivity Research Planning Committee (1981), erosion reduces crop productivity mainly by decreasing the amount of soil water available to plants; this is a result of changing the water-holding characteristics and thickness of the rooting zone. Even for deep-rooted trees, this is a likely consequence of erosion except in deep depositional soils in swales or on terraces. Second, erosion removes nutrients available to plants. Fertilizer applications can partly offset these losses in intensively managed stands, but at greatly increased cost. Third, erosion may reduce productivity by degrading soil structure. Removal of loose, organic surface soils promotes surface sealing and crusting, decreasing infiltration capacity and increasing erosion (see chapter 4, this volume). Fourth, erosion results in loss of important soil biota, such as mycorrhizal fungi, which facilitate nutrient uptake by plants (see chapter 3, this volume).

Surface erosion proceeds downward, removing first the surface layers of organic matter (O horizon), then A horizon material, and so forth. Soil horizons have differing capacities for supplying nutrients and holding water, so loss of productivity is not directly proportional to depth of erosion. Because the highest concentrations of nutrients and biota and the maximum water-holding capacity are in the uppermost soil horizons (Table 5.2, Fig. 5.1), incremental removals of soil nearer the surface are more damaging than those of subsoils.

TABLE 5.2. Distribution of available nutrients and water-holding capacity (WHC), by soil horizon, for a granitic soil in central Idaho. Nutrient extraction procedures are described by Clayton and Kennedy (1985); available water is 0.033 minus 1.5 MPa extractable percentage by volume.

Soil parameter	Soil horizon		
	O	A	C
	-----%		
Potassium	0.11	0.015	0.007
Calcium	1.08	0.052	0.033
Magnesium	0.12	0.006	0.004
Nitrogen	0.57	0.071	0.025
Phosphorus	0.06	0.005	0.002
Sulfur	0.044	0.006	0.004
WHC	—	11.3	4.1

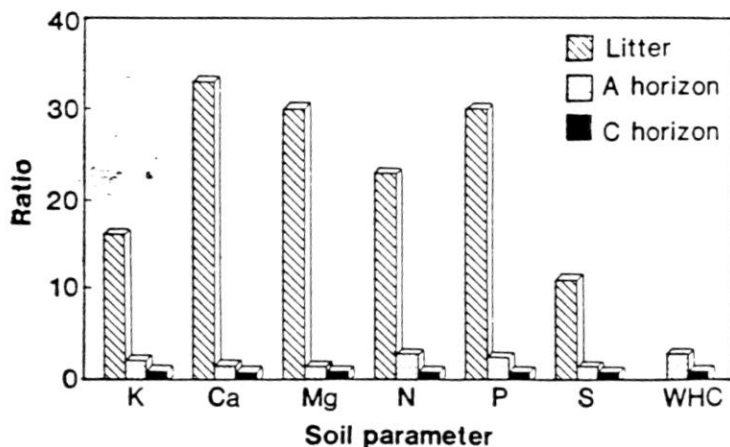


FIG. 5.1. Vertical distribution of nutrient elements potassium (K), calcium (Ca), magnesium (Mg), nitrogen (N), phosphorus (P), and sulfur (S) and available water-holding capacity (WHC) for a granitic soil in central Idaho, expressed as ratios of concentration in the C horizon (soil material relatively little affected by organisms and chemical and physical weathering).

EROSION IN THE NATURAL SYSTEM

In the natural system, soil and sediment move downslope and into streams by a variety of surface erosion processes (Table 5.1), interrupted by periods of temporary storage. Soil is stored on hillslopes behind downed logs, in upturned root wads, and in the soil mantle itself. Bedrock hollows (also termed swales, headwalls, and zero-order basins) are important temporary storage sites that fill slowly over decades to millennia and empty abruptly by small-scale sliding (Dietrich et al. 1982).

These processes of soil transfer and temporary storage are commonly referred to as the sediment-routing system and are quantified in terms of a sediment budget (Dietrich and Dunne 1978, Swanson et al. 1982, Megahan et al. 1986). Comparing sediment budgets of several basins reveals both similarities and differences (Swanson et al. 1987). In the published sediment budgets for the Pacific Northwest, landsliding is a major source of sediment, and surface erosion is of minor importance. However, cohesionless soils formed from granitic rocks (e.g., in the Idaho Batholith) and skeletal soils in general are prone to erosion by raindrop splash and dry ravel, especially when soil strength imparted by roots, mycorrhizae, and other organic matter is reduced (Megahan 1981). Areas with clay-rich soils, such as parts of north coastal California and southwest Oregon, and areas where soil compaction is widespread experience high surface erosion by overland flow and gullying (Kelsey 1980, Kelsey et al. 1981).

Sediment production rates by individual erosion processes, however, are not closely related to site productivity. More relevant measures of erosion impact include the extent of the area affected by erosion; the extent of the affected area that had the potential to grow trees; the water-holding capacity and nutrient and biotic content of the material moved; and the availability of the eroded material to support tree growth elsewhere. Soil creep and deep-seated, slow-moving slumps and earthflows mobilize large volumes of soil, but only a very small fraction of it is removed from potential tree-growing sites. Shallow, rapid debris slides, on the other hand, mobilize smaller volumes of soil, but commonly a large percentage of the moved soil is transported to stream channels. All of these processes of mass soil movement typically involve the entire rooting zone and even subsoil. The average nutrient content of material transported by mass movement processes is lower than that of the nutrient-rich materials transported by surface erosion processes.

Surface erosion processes are also widespread, but scars of debris slides generally cover less than 1 or 2% of slide-prone landscapes (Ice 1985). Soil creep, though widespread, produces little soil disruption, and movement rates are very slow, measured in millimeters per year. Slump and earthflow terrain may cover more than 20% of the landscape, and movement rates may be high enough (greater than 1–2 m/year) to cause severe disruption of forest vegetation, although areas of such rapid movement are rather rare.

In many steep basins, debris slides may be the dominant mechanism of sediment production and downstream damage to fish habitat, but may have only a minor impact on long-term site productivity because they involve small areas. To assess the effects of slide scars on long-term site productivity, we must consider establishment (stocking) and growth of desired species, loss of canopy and rooting space, and percentage of total landscape area occupied by slide scars young enough to have an effect. In a study of 5–18 year old Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] slide scars in the Oregon Cascade Range, Miles et al. (1984) observed 38% less height growth and 25% lower stocking than in restocked clearcuts of the same age. One-third of the area of slide scars (mean area/scar 460 m², range 36–1,287 m²) was estimated to be nonstockable because of unstable or impenetrable substrate. However, Douglas-fir had the highest percentage of cover on slide scars of the more than 140 species identified (Miles and Swanson 1986).

Conditions at this site in the central western Oregon Cascades appear to be more favorable for recovery of commercial forest on slide scars than elsewhere in the Pacific Northwest. In other areas, for example, competition from noncommercial species [e.g., where alder (*Alnus* spp.) establishes dense stands (Smith et al. 1986)], persistent physical instability from surface erosion (e.g., in raveling soils in southwest Oregon), large areas of scars (e.g., common in glaciated terrain), and other factors may considerably slow recovery of commercial productivity on slide scars. This difference has not been quantified to any significant extent, however. Not all areas with high susceptibility to sliding ever had complete cover of commercial species; consequently, assessing productivity losses by comparing slide scars with adjacent, unaffected sites well stocked with conifers may be misleading. Furthermore, establishment of alder, ceanothus (*Ceanothus* spp.), or other nitrogen-fixing, noncrop plants may be an important step in the recovery process.

Active earthflows can significantly affect site productivity as a result of chronic disruption—measurable in terms of the mean angle of lean of trees and percentage of tree stems with curved (“pistol”) butts. In the Douglas-fir forests of the central Oregon Cascades, tree disruption increases with increased earthflow velocity (Vest 1988) (Fig. 5.2). If the land moves more than several meters per year, the conifer overstory breaks up and hardwoods are more prevalent. The tilt and deformation of stems increase progressively with increased earthflow-movement rate (Fig. 5.2).

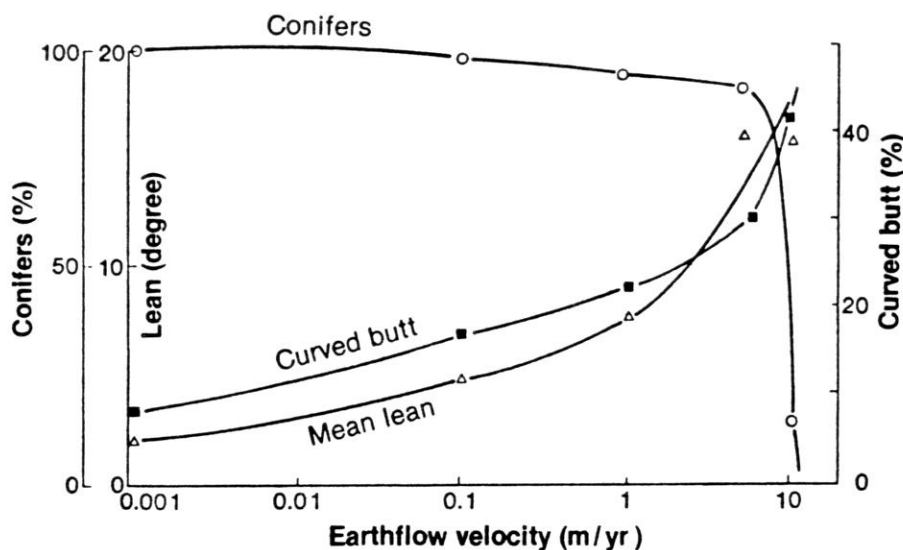


FIG. 5.2. Characteristics of trees in relation to movement rate of earthflow on which they grow (Vest 1988). Mean lean is mean angle between vertical and the axis of stem at breast height (about 1.37 m above the ground). At these sites, the major failure plane of the earthflow occurs well below the root zone.

EROSION IN THE MANAGED FOREST

We have emphasized that erosion is a part of the natural landscape. Forest-management activities alter the natural erosion regime by suppressing some processes, accelerating the rates of others, and introducing some new processes and conditions. This array of effects makes assessing the consequences for long-term site productivity difficult. We review here some of the limited information available on impacts of management on erosion.

Sediment Yield from Small Basins

Paired basin studies have been widely used to assess soil loss as a result of forestry practices. In this approach, two or more basins with similar vegetation, topography, and hydrology are monitored for several years before treatment. After this calibration period, one or more basins are "managed" (treated by logging, road construction, or both), and one basin is left undisturbed as a control. A summary of such data (e.g., Table 5.3, Fig. 5.3) reveals substantial variation in suspended-sediment yield, both in the rates for forested control basins and in the magnitudes of increase resulting from management activities. Increased sediment production following logging and road construction can result from increased availability of material for transport and magnitude of peak flows.

Some of the effects of forest management on suspended-sediment yield can be seen in a comparative analysis of results from experimental basins in western Oregon with at least 5 years of record (Fig. 5.3). This sample, selected to minimize climatic and geologic sources of variation, comprises three groups: basins with gentle (less than 35%) slopes, which yield very low levels of suspended sediment, even after road construction, clearcutting, and broadcast burning; basins with steep (greater than 35%) slopes, which yield higher sediment levels, especially where managed; and basins with steep slopes and debris slides, which yield the highest sediment levels and have among the highest increases relative to their control basins. Generally, suspended-sediment yields increase several-fold after logging and road construction. To put these estimates of sediment yield in perspective, all but the highest values are less than $200 \text{ Mg km}^{-2} \text{ yr}^{-1}$ (about the annual yield of the Siuslaw River at Mapleton, Oregon) but less than one-tenth the annual yield of several rivers in northern California, notorious for their extremely high sediment production due to both highly erodible soils and past forestry practices.

However, observations in the experimental basin studies may not accurately reflect accelerated soil loss from logging and road construction. In several basins, much of the soil delivered to channels by debris slides remained stored there through the period of the published record and was not sampled at the gauging station. Furthermore, sediment that entered the channel and was stored there before basin treatment may have been

TABLE 5.3. Site characteristics and mean annual suspended-sediment yield for six sets of experimental basins in western Oregon for which at least 5 years of data exist for each site condition (Larson and Sidle 1980, Swanson et al. 1987).

Basin name and location	Basin area, ha	Mean basin slope, %	Site condition ¹	Suspended-sediment yield, Mg km ⁻² yr ⁻¹	Period of record, water yr
Fox Creek, Bull Run, N. Western Cascade Mountains					
Fox 1	59	8	R, 25CC, BB	2.9	1972-79
Fox 2	254	8	R	2.0	70-79
Fox 3	71	8	R, 25CC	2.7	73-79
Coyote Creek, South Umpqua River, S. Western Cascade Mountains					
Coyote 1	69	40	R, 50PC	22	72-79
Coyote 2	68	40	R, 30CC	16	72-79
Coyote 3	50	40	R, 90CC, BB	181	72-79
Coyote 4	50	40	F	47	70-79
H. J. Andrews Experimental Forest, Central Western Cascade Mountains					
HJA 1	96	63	F	8	57-61
HJA 1	96	63	100CC, BB	183	67-76
HJA 2	60	61	F	11	57-76
HJA 3	101	53	R, 25CC, BB	456	65-76
HJA 6	13	28	R, 100CC, BB	13	76-79
HJA 7	15	31	50PC	2.5	72-79
HJA 8	21	30	F	11	72-79
HJA 9	9	60	F	3.4	69-79
HJA 10	10	60	F	9.5	76-79
HJA 10	10	60	100CC	57	76-79
Alsea River, Coast Range					
Deer	303	50	F	97	59-65
Deer	303	50	R, 25CC, BB	136	66-73
Needle	71	37	F	53	59-65
Needle	71	37	90CC, BB	146	66-73
Flynn	202	50	F	98	59-73

¹F = forested, R = roaded, 50CC = 50% of area clearcut, BB = broadcast burned, 50PC = 50% of stand removed in partial cut.

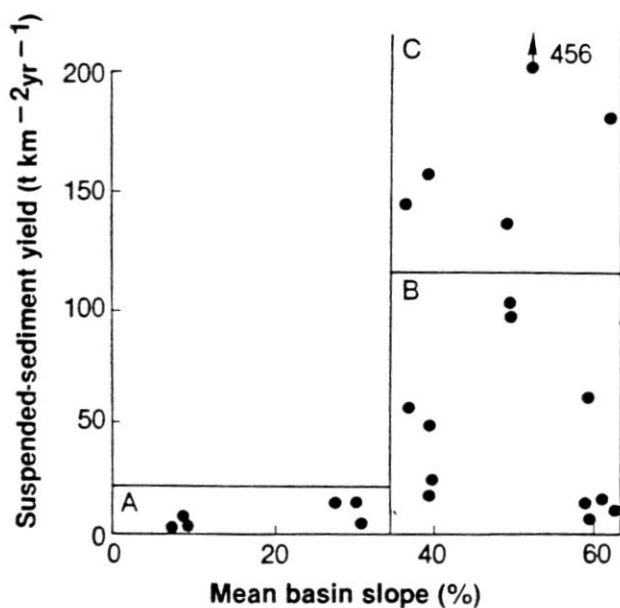


FIG. 5.3. Summary of annual suspended-sediment yield for small experimental basins in western Oregon with at least 5 years of record for forest or treated conditions. (Data are from Table 5.3.). Group A: gentle slopes; 0-100% logged, burned, roaded. Group B: steep slopes; 0-100% logged, roaded. Group C: steep slopes and debris slides; 25-100% logged, burned, roaded.

released when large woody debris was manipulated during logging and road construction. Increased sediment yield resulting from release of this material does not represent soil erosion accelerated by management practices.

In summary, although studies of small experimental watersheds reveal substantial increases in sediment yield after timber harvest and road construction, interpretation is complicated by the importance of localized sediment sources and sites of deposition. The basins with the greatest increases in sediment yield experienced soil and sediment movement by debris slides and debris flows. Slides mobilize material in localized parts of a drainage basin; so soil and sediment volume, even if large, may not represent widespread loss of site productivity. Debris flows may also mobilize large volumes, but most of it may be material that entered the channel previously and had already been removed from the soil mantle used by the growing forest crop. None of the published sediment-budget studies has been designed to consider site-productivity issues specifically.

Debris Slides

Clearcutting and road construction generally increase the frequency and areal extent of debris slides (Ice 1985). However, the proportion of Pacific Northwest landscape in slide scars less than 10–30 years old is generally less than a few percent, even after a major storm that triggers many debris slides (Ice 1985). Moreover, slide scars in this region have little tendency to expand, although some undocumented cases of expansion have been reported. Elsewhere in the world, slide scars have been known to expand progressively to cover 20% or more of the landscape and reduce site productivity over substantial areas. In New Zealand, for example, where volcanic ash mantles steep, hilly country, heavy grazing combined with periodic intense rain storms have progressively stripped the soil developed in the ash from the slopes (Crozier et al. 1980). The initially small slide scars have grown by lateral and headward expansion over a series of large storms. The new soil-vegetation-erosion regime established as a result of management practices (conversion of forest to pasture and subsequent intensive sheep grazing) has resulted in a 21% decrease in site productivity on old slide scars as long as 75 years after sliding (Trustrum et al. 1983). In the area as a whole, total productivity has dropped 16%.

Are current forestry practices in the Pacific Northwest likely to produce similar changes in system function and productivity? Probably not of the type observed in New Zealand, where vegetation type was completely converted on slide-prone soils. But our management practices may change the frequency and size distribution of slides—which may have a greater effect on stream and riparian (streamside) resources than on timber production. This view is based in part on the hypothesis that debris slides in many areas of the Pacific Northwest originate in bedrock-defined depressions (hollows) on hillslopes, which fill slowly and fail periodically, triggering debris slides and flows. In this view, sliding is restricted to those hollows; and because hollows occupy a small percentage of the total landscape area, loss of site productivity is not expected to be widespread.

Debris slides related to roads can occur on landforms that would have little chance of sliding otherwise. By contributing to occurrence of slides, roads further increase the amount of land removed from timber production. Furthermore, slide scars from failed road fills may be slower to recover site productivity than slide scars elsewhere on the landscape because they are less likely to receive material sloughed from adjacent, intact soil and are subject to repeated surface erosion from road runoff. The road surface at the head of a road-fill slide scar may be a source of infertile material that disturbs vegetation recovery on the slide scar rather than enhancing it, as would be true for slide scars with natural soil in the headscarp.

Surface Erosion

Sediment-budget studies suggest that surface erosion, although not a major source of sediment in many forested watersheds, may have disproportionately large significance in terms of site productivity because it is widespread and affects the nutrient-rich surface of the soil. Overland flow and rill erosion produced by overland flow are rare under forest cover in the Pacific Northwest, but are common where soils are compacted or where they are hydrophobic (water repellent) as a result of wildfire or slash burning.

Effects of timber harvest and site preparation on surface erosion have been examined in a few studies of limited scope in the region. A summary of some research at the H. J. Andrews Experimental Forest, near Blue River, Oregon, and neighboring areas of the Willamette National Forest provides examples of the type, duration, and magnitude of effects of forest practices on surface erosion (Tables 5.4, 5.5) (Swanson and Grant 1982). Conducted by different workers using different methods and with different objectives, these studies are not strictly comparable, but do reveal important trends. All studies used erosion collector boxes open on the upslope side; overland flow, if it existed, was usually not sampled. Erosion rates are expressed per unit area,

TABLE 5.4. Description of surface erosion studies in Oregon's Willamette National Forest (Swanson and Grant 1982). Surface erosion data are summarized in Table 5.5. Entries without citations are unpublished data on file at the Forestry Sciences Laboratory, Pacific Northwest Research Station, USDA Forest Service, Corvallis, Oregon, which is the affiliation of all the investigators who furnished unpublished data.

Investigators	Site location ¹	Slope range, %	Length of record, yr	Number of erosion boxes	Width of box opening, m	Contributing catchment area, m ²	Frequency of collection, no./yr
Mersereau and Dymess ² (1972)	HJA 1	60-80	1.18	10	2.45	62-262 (range)	6
G. W. Lienkaemper and F. J. Swanson ³ Stream Team ⁴	HJA 1	60-80	1.00	8	2.10	63-262	8
	HJA 9	26-55	5.50	34	0.5	— ⁸	8
	HJA 10	26-55	2.15	34	0.5	— ⁸	8
F. J. Swanson ⁵	HJA 10	26-55	0.87	34	0.5	— ⁸	12
F. M. McCorison ⁶	Site VI	80	3.00	1	16.5	776	4
	Sites I, II	95-100	3.25	2	15.7-20.2	214-458	4
	Sites III-V	80-88	3.00	3	8.9-9.6	124-171	4
George ⁷ (1984)	SFM	19-61	1.00	24	1.5	2.3	4

¹HJA 1-10 = H. J. Andrews Experimental Forest watershed number; SFM = Ryder Creek, South Fork McKenzie River.

²Results given by aspect, slope, and duff cover conditions.

³Follow-up study to Mersereau and Dymess (1972) 12 years after burning; erosion boxes in about the same location as before.

⁴Research group at Oregon State University, Corvallis. Erosion boxes placed in clusters along 1400-m stream perimeter.

⁵Erosion boxes placed at 20-m intervals along stream perimeter.

⁶All sites selected to represent maximum surface-erosion rates for forested conditions.

⁷Results given by slope and duff cover; duff removed by burning; site artificially cleaned of slash.

⁸Unbounded erosion boxes; contributing area not determined.

TABLE 5.5. Surface-erosion data, by slope class and treatment, for studies in Oregon's Willamette National Forest (Swanson and Grant 1982). Study descriptions and affiliations of those furnishing unpublished data are summarized in Table 5.4.

Slope class, %	Annual surface-erosion rate, m ³ ha ⁻¹ yr ⁻¹				
	Undisturbed forest	Clearcut, unburned (2 yr after treatment)	Clearcut, unburned (1st decade)	Clearcut, burned (2 yr after treatment)	Clearcut, burned (1st decade)
0-30 ¹	6.9 × 10 ⁻⁷	0.0018	0.00088	0.10	0.050
31-60	0.014 ²	0.18 ³	0.11	0.57 ⁴	0.32 ⁵
60+	0.19 ⁶	—	—	2.9 ⁷	1.6 ⁸

¹All values for this slope class, except that for clearcut, unburned sites (first decade), are averages from George (1984); the value 0.050 is the average of 6.9 × 10⁻⁷ and 0.10.

²Average of streamside erosion boxes, watersheds 9 and 10, and upslope boxes.

³Average of Stream Team (unpublished data; see footnote 4, Table 5.4) and George (1984; first year after cutting).

⁴Average of George (1984; clearcut, burned sites) and Mersereau and Dymess (1972; sites 5-8).

⁵Average of Mersereau and Dymess (1972) and G.W. Lienkaemper and F.J. Swanson (unpublished data; sites 5-8).

⁶Average of F.M. McCorison (unpublished data; sites I-IV).

⁷Average of Mersereau and Dymess (1972; sites 1-4).

⁸Average of Mersereau and Dymess (1972) and G.W. Lienkaemper and F.J. Swanson (unpublished data; sites 1-4).

based on estimates of contributing area above the collector, except on watersheds 9 and 10 (H. J. Andrews Experimental Forest); in these two watersheds, erosion boxes were located along the stream edge, and soil delivery to the channel was estimated by multiplying the average rate of soil collection per meter of channel perimeter by the total stream perimeter. Surface erosion per unit of hillslope area was then estimated by dividing by total watershed area (9 ha for watershed 9, 10 ha for watershed 10).

Summarized mean surface-erosion rates for various sites and treatments exhibit expected trends (Table 5.5), despite great variability in surface erosion rate among erosion boxes at individual sites. For example, in forested watershed 9, 30 of 47 sample periods had 40% or more of the total soil collected in only one of the 33 erosion boxes. Surface erosion rate greatly increased with increasing slope gradient and was much higher in burned than in unburned clearcuts (Table 5.5). Within 5 years of clearcutting without burning, surface erosion rate (organic + inorganic material) measured at watershed 10 (Fig. 5.4), a steep (average slope gradient = 65%) drainage with hillslopes extending directly to the stream banks along much of their length, appears to have stabilized at about $0.07 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, which is about 3 times the rate observed in the forested control, watershed 9. At such sites with moderate disturbance (skyline yarding, no broadcast burning), the period of accelerated surface erosion appears to be brief, relative to the rotation length of 80–100 years.

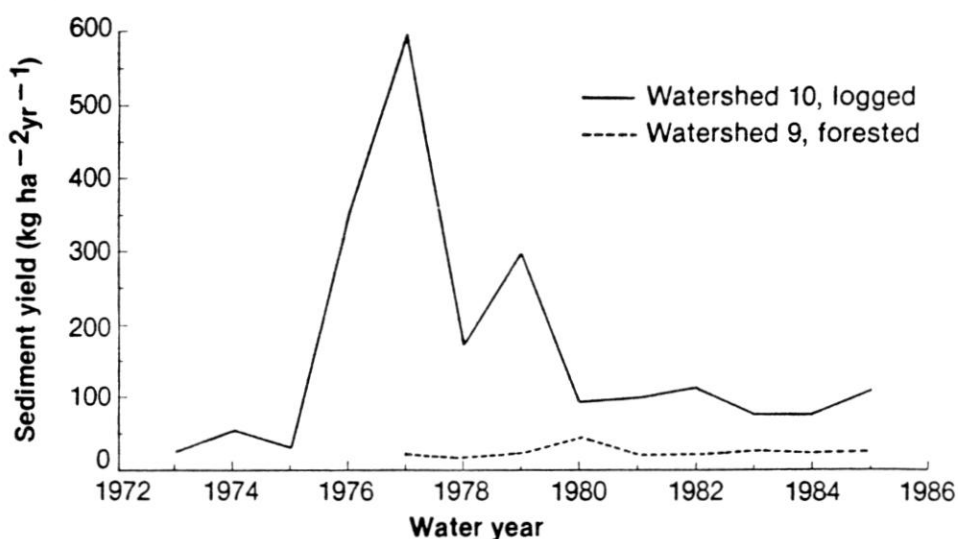


FIG. 5.4. Surface erosion rates 1973–85 for watersheds 9 (forested control) and 10 (clearcut June 1975 without broadcast burning), H. J. Andrews Experimental Forest, Oregon Cascades.

Elsewhere in the region, other types and magnitudes of surface erosion have been observed. Rates of soil ravel are very high in the Oregon Coast Range during and following slash burning on loamy soils developed on the Yachats Basalt Formation and on clay loam to gravel loam soils in sedimentary rocks of the Tyee/Flournoy Formation. Sampling over the first year after burning, Bennett (1982) measured surface erosion at $176 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ on burned clearcuts with slopes over 60%, $22 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ on gentler slopes. Unburned clearcut slopes steeper than 60% lost $13 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. On the steep, burned sites, 65% of the first year's erosion occurred in the 24-hour period including the fire; the high rates of the immediate post-burn period declined after 8 months to $6.2 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ and returned to preharvest levels after 2 years. No surface erosion was detected in four erosion boxes placed in the forest.

Surface erosion by ravel is also locally severe in the Klamath Mountains and Idaho Batholith where skeletal soils are widespread. Where roads, streams, and small slide scars cut a steep slope, soil removal to a depth of 1+ m by raveling can progress upslope for distances of 50 m and more over several decades. The rate and extent of soil raveling appear to be greatest where vegetation has been severely disturbed by clearcutting and hot slash burning. Studies of pervasive surface ravel are underway by D. McNabb (McNabb 1985) and by H. Froehlich and M. Pyles (Oregon State University) as part of the Forestry Intensified Research (FIR) program in southwest Oregon. McNabb (1985) observed a 42-fold increase in ravel rate during the harvest period relative to preharvest and control rates, but the ravel rate for 5 post-harvest summer months differed little from that before harvest. Ravel over the following winter declined to half the preharvest rate, a pattern McNabb interprets to be a result of the unburned slash stabilizing the soil surface. The percentage of organic debris in the transported material doubled from before to after harvest (from 10 to 22%), but the relative abundance of coarse and fine fractions changed little.

Several of these studies can be compared on the basis of movement rate of soil into erosion boxes, expressed as soil mass per length of collector opening per unit of time (Table 5.6). The clearcut and burn treatments on steep (greater than 60%) Coast Range slopes produced by far the greatest rate of surface erosion. Unfortunately, no other sites are available with full measurements for the first year after clearcut and burn treatments on slopes greater than 60%. Cutting without burning substantially increased surface movement rate in two of the three cases.

TABLE 5.6. Surface erosion for forested areas in Oregon and Idaho for 1 year after treatment, expressed as grams of organic and inorganic soil collected per meter of contour line per day¹.

<i>Erosion study sites, by treatment and slope gradient</i>	<i>Number of erosion boxes</i>	<i>Surface-erosion rate, g m⁻¹ day⁻¹</i>
>60% Slope		
Undisturbed forest		
Coast Range	4	0
Klamath Mountains	6	9
Cascade Range	30-34	0.4
Clearcut, burned		
Coast Range	24	230
Clearcut, unburned		
Coast Range	4	33
Klamath Mountains	19	7
Cascade Range	34	8
<60% Slope		
Clearcut, burned		
Coast Range	8	8
Idaho Batholith	11	0.5

¹Assuming bulk density = 1.0 g/cm³, except for Idaho Batholith, where bulk density = 1.3 g/cm³. Coast Range from Bennett (1982), Klamath Mountains from McNabb (1985), Cascade Range from the H. J. Andrews Experimental Forest (G. W. Lienkaemper and F. J. Swanson, unpublished data, Pacific Northwest Research Station, USDA Forest Service), and Idaho Batholith from Clayton (1981).

The data summarized in Table 5.6 are for the first year after treatment only. Studies covering longer periods typically have found higher surface-movement rates in the second year after treatment (Clayton 1981, George 1984; D. McNabb, personal communication, Oregon State University, 1987) (Fig. 5.4). Several workers have speculated that decomposition of slash may be a factor. If so, surface erosion rates for sites that lose fine litter when burned probably peak earlier than those for unburned sites.

Even modest rates of downslope movement of slash and soil, perhaps with the help of the downhill creep of a snowpack, can damage seedlings, resulting in substantial loss of management investment and perhaps delayed regeneration. The title of an early paper on the subject—"Are your seedlings being buried?" (Franklin and Rothacher 1962)—raises the issue. In the only recent study, McNabb (1986) observed minor ravel-related mortality of seedlings on a steep, clearcut, but unburned site. In this case, use of ravel guards to protect seedlings was unnecessary.

In summary, surface erosion is important to site productivity because it can be widespread and may retard reforestation. As pointed out by Rice et al. (1971), burning is the major factor in accelerating surface erosion where cable yarding has been used. Results of studies indicate that the period of accelerated surface erosion is generally short relative to the rotation length. Unfortunately, we have few samples of surface erosion rates in areas experiencing wildfire and its erosional aftermath as a point of reference for judging effects of forestry practices [the work of Megahan and Molitor (1975) is a notable exception].

Forest Roads

Forest roads can have significant effects on site productivity through mechanisms of both site disturbance and erosion. In a recent review paper, Megahan (1988) summarizes results of published and unpublished studies on effects of roads on the area removed from timber production and on road-related impacts on hydrology and soil properties that influence tree establishment and growth. He finds that road construction can initially affect 1-30% of the landscape—much of which may be available for tree growth after construction. Site conditions are poorest on the cut portion of the road bed and backslope, but tree height growth is typically no

different for fills and adjacent areas. Growth may be greater on fill slopes than on undisturbed slopes in some locales. Cutslopes and road drainage to downslope areas can increase or decrease productivity, depending on local site conditions and the importance of water as a limiting factor in tree growth.

Generally, Megahan (1988) concludes that productivity loss is less than that reflected in the area directly affected by initial road construction. At some sites, however, debris slides and substantial modification of the ground-water system translate road impacts up and down the slope.

LONG-TERM CONSIDERATIONS

Stability or change in site productivity must be evaluated on the scale of thousands of years, because this is the scale of soil development. The residence time of soil on steep slopes in a small Cascade Range drainage basin, for example, is about 10,000 years, assuming average soil thickness of 1 m in a 10-ha basin divided by average annual export of 1 m³/ha for soil and sediment with bulk density of 1,000 kg/m³ (Swanson et al. 1982). Important considerations at this time scale include the effects of management practices on the rate of soil formation by processes such as weathering and the rate of soil loss, including that induced by vegetation disturbance. Unfortunately, very little is known about the effects of forestry on soil formation in Northwest forest soils. A bit more is known about the effects of disturbance on soil erosion rates, so we will discuss this subject briefly.

Ultimately, analysis of long-term site conditions must consider the natural disturbance regime of the landscape. By disturbance regime, we refer to the characteristic types, frequencies, intensities, and durations of events that alter vegetation and soil properties. Forestry replaces the natural disturbance regime (wildfire, "blowdown," landslides) with a management disturbance regime (harvest, roads, prescribed fire, vegetation control).

In many steep areas, an important part of the long-term soil loss occurs in pulses of erosion after vegetation has been disturbed. Swanson (1981) suggested a simple approach to evaluating the effect of a disturbance regime on soil erosion by assessing the frequency, magnitude, and duration of an erosion peak resulting from a disturbance such as wildfire. The amount of erosion produced by a series of disturbances is compared to the baseline erosion in the period between peaks, yielding a measure of the contribution of major vegetation disturbances to the long-term erosion rate. On the basis of some simple assumptions, Swanson (1981) estimated that wildfire-accelerated erosion accounted for about 23% of long-term erosion in the central western Cascade Range. In a chaparral system with more frequent, intense fire and greater erosional response to fire, about 75% of the long-term erosion rate was apparently fire related. Depending on the frequency and intensity of vegetation disturbance, as well as the sensitivity of a landscape to erosion, a particular area may have greater or lesser erosional response to disturbance.

Consideration of the frequency and magnitude of episodes of accelerated erosion is a useful frame of reference for discussing the effects of forestry on erosion and site productivity. Soil erosion and site productivity in ecosystems where the management disturbance regime differs negligibly from the natural disturbance regime are likely to remain basically unchanged. We know little about natural disturbance regimes, however, and even less about their effects on soil for many ecosystems where intensive forestry is being practiced. In the Douglas-fir forests of the western Oregon Cascades, for example, the perception of the natural fire regime is now changing substantially. These forests were thought to have experienced very infrequent (return period of several centuries), widespread, stand-replacement fires as the dominant element of the disturbance regime. Recent field studies (Morrison 1984, Stewart 1986, Teensma 1987) suggest that more frequent (return period of about 100 years) fires of moderate and low severity are an important part of the disturbance story.

In summary, an important, neglected ingredient in analyzing effects of forestry on site productivity is management of changes in the disturbance regime on the scale of centuries before and after first entry. From a management perspective, we should be concerned about changing the natural disturbance regime on sites sensitive to erosion. For instance, steep areas in which vegetation and soils have developed in a regime of frequent, low-intensity, short-duration fire may experience severe erosion problems as a result of slash burning; if unusually prolonged, high soil-surface temperature kills sprouting brush species, destroys soil structure stabilized by organic matter, and disturbs other soil-stabilizing mechanisms. In central Idaho, Steele et al. (1986) observed that, before 1895, the fire regime was dominated by low-severity fire at 10–20 year intervals. Suppression efforts since then have lengthened the interval, but increased the potential for severe, stand-replacement fires which can substantially reduce long-term site productivity.

CONCLUSIONS

Although forestry practices in the Pacific Northwest can accelerate soil loss, erosion alone is seldom the cause of greatly reduced site productivity, except on slide scars and sites of persistent ravel, which are generally local in extent. On severely disturbed sites, however, erosion acts in combination with other factors to reduce productivity on the scale of decades to centuries. Extreme disturbance by intense wildfire or tractor yarding, for example, may cause loss of nutrients, mycorrhizae, and organic matter. These losses not only reduce long-term site productivity, but may also lead to sustained periods of accelerated erosion because the soil-stabilizing effects of live and dead organic matter are reduced or even eliminated. The two major influences of erosion processes in such cases are to remove soil and chronically disturb sites, thus delaying establishment. By these mechanisms, severe disruption can exceed thresholds of ecosystem resistance both physically and biologically. Under these conditions recovery will likely be slow, initiated perhaps in localized patches (relatively "safe sites"), stabilized by structures such as stumps, clumps of residual vegetation, large woody debris, and rock outcrops. Furthermore, a significant amount of soil development will be required to replace lost soil and recover degraded soil properties.

The short-term (year to decade) effects of erosion on site productivity are generally not dramatic in this region of low-intensity precipitation and rather rapid revegetation. Longer term effects of erosion are poorly understood and difficult to interpret from studies of erosion after harvest of natural stands, which leaves much greater amounts of residual vegetation and woody litter than would be likely from future harvest of managed stands. To evaluate long-term effects of erosion on productivity of managed sites, we need further field studies coordinated with modeling to simulate long-term aspects of system behavior (see chapter 11, this volume). Thus far, study of long-term development of forest soils in the region has been sketchy, and little effort has been made to incorporate erosion into the analysis of long-term site productivity.

The best recommendation for managing the soil resource is to be judicious with the disturbance regime, especially with fire and physical disruption of the soil. Poor forestry practices can trigger long-term degradation of site productivity. We believe that in most areas where sound, modern forestry is practiced, accelerated erosion alone is unlikely to cause widespread, major loss of long-term productivity.

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QUESTIONS FROM THE SYMPOSIUM FLOOR

- Q: If Coast Range headwalls have no trees to leave, should trees be left upslope from the headwall and, if so, how many?
- A: The major argument for establishing headwall "leave areas" (patches of forest or shrub vegetation) has been to preserve root strength in order to reduce occurrence of landslide associated with clearcutting. From this point of view, cutting trees at the upper edge of an unstable headwall basin may not directly impact the slide-prone area. There also may be hydrologic and other stabilizing influences of vegetation left in headwall basins, but these have not been studied. Felling and bucking of trees above headwalls may reduce stability of slide-prone parts of headwalls by direct physical damage caused by sliding logs, and through slash accumulation which suppresses revegetation and increases the possibility of slash fires burning into the headwall area.
- Q: How does removing large woody debris (commonly referred to as YUM yarding or gross yarding) from steep harvested sites (to lessen broadcast burning intensity) affect erosion rates? Is it a good trade-off?
- A: I would favor leaving large woody debris and timing the burning (e.g., spring rather than fall burning) to keep the fire intensity down so that nutrients and sediment-trapping structures are retained.
- Q: If you have an active slide within a proposed timber-sale boundary, what preventive measures do you suggest prior to harvest, particularly if the slide area cannot be deleted from the harvest area?
- A: If it is a shallow slide (failure plane 1–2 m deep), consider managing the root systems, such as leaving brush and hardwoods around the slide perimeter. If it is a deeper slide (earthflow or slump), consider managing the hydrology of the site by, for instance, road drainage systems to divert water from upslope areas or from the slide surface itself.

- Q: Considering the Coast Range headwalls are often geologically weak areas that naturally tend to seed to alder—a deep-rooting species that probably tends to further chemically and physically weaken the site—would it not be better to do something like plant Douglas-fir just outside the area and species like hemlock (*Tsuga*), Sitka spruce [*Picea sitchensis* (Bong.) Carr.], and western redcedar (*Thuja plicata* Donn ex D. Don) on the area? Thus the root mat over the headwall would be anchored to the Douglas-fir on the edge.
- A: The jury is still out on whether headwall leave areas prevent management-accelerated sliding (Swanson and Roach 1987). Such suggestions are interesting to discuss, but we are a long way from knowing if they would be worth the investment. Ziemer (1981) has examined the relative root strength of a number of species and found that many brush species have relatively high strength.
- Q: On steep coastal slopes, do you advocate gross yarding of draws to reduce occurrence of debris flows and probable debris dams?
- A: Some very large, stable pieces of woody debris in draws may help to stabilize them by preventing release of accumulated finer slash that could trigger debris flows downstream. The best practice is to keep slash out of highly sensitive sites in the first place.
- Q: Regarding erosion and landsliding, have you studied the effects (increased erosion and slides) of the second year following clearcutting and broadcast burning on steep slopes? Studies on the Entiat Experimental Forest (east slope of the Washington Cascades) show increased slump and slide activity the second year following wildfire.
- A: The actual year of sliding after a fire or clearcutting is probably determined more by storm history than anything else. However, the timing of sliding appears to vary in a broadly systematic fashion after disturbance, presumably as a result of declining strength of decaying roots of killed vegetation and the lag before roots of invading vegetation fully reestablish a root network. A study in Mapleton in the Oregon Coast Range, for example, found 63% of slides occurring 0–3 years after logging and burning, 29% 4–10 years, and 6% 11+ years. In the Oregon Cascades (Swanson and Dyrness 1975), the values were 46, 42, and 12%. In the Idaho Batholith (Megahan et al. 1978), they were 24, 41, and 35%. The apparent delay in sliding in the more interior areas may reflect slower revegetation and decomposition resulting from colder winters and drier summers.
- Q: Logging roads are frequently built on the lower slopes of steep-sided valleys. Has there been any research to examine how these roads may affect the flow of water and nutrients to the lower slope sites and, ultimately, the long-term productivity of these productive ecosystems?
- A: The paper by Megahan (1988) summarizes the scanty and anecdotal information on this subject. There has been too little research to make a general statement.
- Q: On slopes with a history of debris slides, have you noted differences in soil profile characteristics or degree of development within bedrock hollows vs. more stable positions on the same slope? If so, does this indicate any degree of hazard?
- A: To my knowledge this has not been studied systematically. Some textural properties and radiocarbon dates of soils filling hollows have been examined (Dietrich et al. 1982, Reneau et al. 1986), but with little comparison to “nonhollow” soils. I believe that landform (steepness of axis and sideslope of hollow) and soil thickness are key criteria for judging debris-slide potential of a site.
- Q: When quantifying soil loss due to surface erosion, how much loss is significant and how much can be replaced through natural soil building within an 80-year rotation?
- A: As discussed in the chapter, we have no information on the soil-loss tolerance of forest ecosystems.
- Q: You mentioned that the Drift Creek slide in the Coast Range was an example of a natural mass movement. Is there any disagreement among researchers as to whether road construction had any effect on the timing or magnitude of the slide?
- A: I have heard no discussion of this question, but personally consider it possible, though not probable, that the road and logging contributed to catastrophic failure at Drift Creek.
- Q: What do you think of grass seeding as a measure to prevent surface erosion or mass movement?
- A: Establishing grass can locally reduce surface erosion; however, its potential effectiveness depends on timing of seeding relative to heavy rains, nutrient status of treated soils, and other factors. I believe that grass seeding has no significant effect on sliding in the Pacific Northwest landscape.
- Q: Have the multirotational European forests seen an increase or decrease of erosion landslides over time? Does this relate to a decrease in organic matter?
- A: I know of no data on the subject. The issue of the effects of Waldsterben (forest decline) on erosion and runoff is now being confronted by the Europeans, and results of a small workshop and brief field exercise on this subject were recently published by the Swiss government.

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