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The Impact of Timber Harvest, Fertilization, and Herbicide Treatment on Streamwater Quality in Western Oregon and Washington

R. L. FREDRIKSEN, D. G. MOORE, and L. A. NORRIS

OLD-GROWTH DOUGLAS-FIR FORESTS are famous for their natural beauty and for the excellent quality of the streams that flow from them. Domestic water supplies from municipal watersheds often require no treatment beyond chlorination. Salmon and steelhead trout, which provide a valuable commercial and sport fishery, use these streams for spawning and rearing areas for their progeny.

Roughly 20 to 30 years ago, after most of the timber had been cut from more accessible stands on gentle topography, logging operations began to move into the mountainous Cascade and Coast Ranges of western Oregon. An increasing percentage of Oregon's softwood supply has since come from this mountainous topography. Most of this land is managed by the U.S. Forest Service and the Bureau of Land Management. In 1972, 7.5 million cubic meters of softwood was harvested from the National Forests in western Oregon.

Timber harvest operations can seriously degrade the quality of streamwater. Soil disturbance by forest roads crossing steep slopes and unstable soils can markedly increase soil erosion and stream sedimentation. Rapid decomposition of logging residue can also increase the concentration of nutrients in streamflow.

The rapid regrowth of forest vegetation, necessary for the future timber supply from these lands, is an important deterrent to soil erosion. Fertilizers are now commonly used to achieve rapid growth of young Douglas-fir stands. Approximately 150,000 ha of forest land have now been fertilized in the Pacific Northwest, and over 40,000 ha are being fertilized each year. Herbicides are also applied to young forest stands to reduce the excessive competition of brush. Fertilizers and herbicides are valuable tools, but their use can reduce water quality.

Man's use of mountainous areas of the Pacific Northwest has become a key resource management issue. The current debate over clearcutting is

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R. L. Fredriksen is Soil Scientist, D. G. Moore is Research Soil Scientist, and L. A. Norris is Supervisory Research Chemist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest & Range Experiment Station, Forestry Sciences Laboratory, Corvallis, Oregon.

evidence of a need for a more equitable assignment of values among various resources of this land. Because streamwater quality represents the integrated effect of man's activity in the forest, water quality standards have been established in the Pacific States. The effect of these standards is to regulate forest management activities which have severe impacts on streams.

This paper describes the impacts of forest management practices on streamwater quality in the Douglas-fir region. We present (a) a conceptual base for understanding the processes of soil erosion and stream sedimentation and the outflow of native nutrients, fertilizers, and herbicides in streams, and (b) recent research findings from Cascade and Coast Range watersheds which illustrate these concepts.

Method and Design of Watershed Studies

Small experimental watersheds are commonly used to measure the effects of different kinds and intensities of forest management on water quality of streams. Sets of watersheds are selected that are typical of regional forest types and that are as similar as possible in soil, parent material, and vegetation. Baseline water quality is determined by sampling the streams for one or more years before treatment. Forest management alternatives are selected that represent present or improved practices of logging, logging residue management, regeneration, and culture of the subsequent forest. After treatment, water quality is sampled for a period of years to determine the maximum changes that occur and the time required before water quality indices return to pretreatment levels. These changes are determined by comparison of streamwater quality from managed watersheds with water quality from an undisturbed control watershed. Watershed studies measuring changes in water quality are of greatest value when coupled with an understanding of how management practices affect the physical and biological processes that supply soil and chemicals to streams.

Soil Erosion Leads to Stream Sedimentation

Erosion is the process whereby soil is moved downhill and is often delivered to streams. Soil erosion can be controlled by the management given the land; therefore, a review of soil erosion in relation to timber harvesting practices precedes the discussion of stream sedimentation.

Natural Processes

In the Pacific Northwest, the Coast Ranges and the western-facing slopes of the Cascade Range have a rapid geologic erosion rate characteristic of

mature mountainous regions composed of igneous parent materials forming unstable soils and receiving heavy amounts of precipitation. Because streams lose roughly 1,500 m of elevation in a distance of 80 km, and because of a large winter runoff, the energy of streamflow is capable of transporting eroded material deposited in stream channels. As a result, many second- and third-order streams draining undisturbed watersheds run entirely on bedrock.

Post-Pleistocene erosion has been cyclic and episodic in nature. Short periods of accelerated erosion and increased stream sediment loads, probably after holocaustic wildfires, were followed by periods of relative stability lasting up to several hundred years. Erosion following vegetation denudation was undoubtedly the result of long-term geomorphic and pedogenic processes. These include deepening of the unconsolidated mantle on slopes by mineral weathering and secondary mineralization, including clay mineral formation, redistribution or loss of materials on slopes by surface creep movement or high velocity landslides, and slope steepening by channel incision (3). Denudation of vegetation from slopes is not always a prerequisite to slope failure. Where movement of the unconsolidated mantle is rapid, mass soil erosion events may result where there is a cover of mature forest vegetation (10).

Hill slopes covered with natural forest vegetation are remarkably stable in this region, even though soils and saprolite of medium to fine texture and 10 m or more in depth may occur on 80% slopes. Stability results from a unique combination of vegetation, soil, and climate. The nearly complete cover of Douglas-fir forest vegetation and forest litter dissipates the energy from low-intensity precipitation characteristic of the region, and tree roots strengthen soil on slopes (3). Runoff from long-duration winter storms flows entirely through the soil mantle because of rapid infiltration and percolation rates which greatly exceed the precipitation rate (12). Surface runoff occurs only for a few hours during winter storm events in ephemeral stream channels and at the zone of saturation along streams.

Thus, we conclude that the principal means of slope erosion is by the mass movement of soil—the end product of a long-term train of events. This erosion process is commonly associated with winter rainstorms which temporarily load the soil with detained water and at the same time decrease the mantle shearing resistance (44). Expanding lattice clays at the shear zone within the soil mantle increase the frequency of landsliding (38). Though there are landslides reported at intervals of 3 to 4 years, landslides remove the largest soil volume at the time of exceptionally high streamflow resulting from long duration rainstorms which may also include snowmelt; these have occurred with major flooding at intervals averaging 17 years since 1861 (15).

Impact of Forest Management on Soil Erosion

Of all forest management activities, roads cause the greatest soil disturbance in steep, mountainous topography. Erosion from truck roads, clearcuts, and undisturbed areas was compared at the H. J. Andrews Experimental Forest (2, 10). Another study (42) found that during road construction, vegetation was removed and soil disturbed on 6.2% of the land; landings, where logs are loaded on trucks, disturbed an additional 3.6%. Where roads are near streams, soil cast aside on steep slopes may reach streams. Redistribution of drainage water and soil on steep slopes often leads to accelerated soil erosion and sedimentation of streams. Of all forest roads, midslope roads—those which traverse steep mountain slopes and cross small, deeply incised tributary streams—cause the greatest soil erosion and deterioration of water quality from stream sedimentation. The erosion rate is lower from roads located on more stable topography such as river terraces and ridgetops.

Of the soil erosion processes triggered by forest roads, mass soil erosion moves much more soil than is removed from the surface of road cutbanks and fill slopes. From one study in western Oregon, the mean annual soil loss over a 5-year period from the surface of bare backslopes was 0.9 cm per year.[1] A similar or higher rate of erosion can be expected from fill slopes. In a nearby 101-ha watershed, mean annual soil loss for a 9-year period was 2,330 m^3/km^2 where road cut and fill slopes occupied 4% of the watershed area; the soil was lost mainly by landslide erosion (16). If only half of this soil volume came from the roads—a conservative estimate—and this volume was applied to the area of the road right-of-way, the calculated annual soil loss of 7.5 cm is roughly eight times greater than the surface erosion of backslopes. Because the surface soil erosion of cut and fill slopes can be reduced by revegetation, the importance of mass soil erosion on water quality may assume a greater importance than is indicated by these figures (13).

A much greater volume of soil has been removed in association with forest roads than with either clearcut or undisturbed areas. In 1964, following one severe storm, 266,000 m^3 of soil was moved by 47 landslides from a 6,100-ha drainage (10). Nearly 64% of the soil entered stream channels, creating water quality problems. Based upon the area occupied by roads, clearcuts, and undisturbed sites, the volume of soil removed due to road-connected landsliding was 62 times greater (1300 m^3/ha) than the volume removed from unroaded clearcut and undisturbed areas (21 m^3/ha for each). Mass movements from this storm were 300 times more frequent from roads and 10 times more frequent from logged areas than from the undisturbed forest. However, the volume of mass movements from undisturbed sites was 5 to 10

[1] *C. T. Dyrness, U.S. Forest Service, Forestry Sciences Laboratory, Corvallis, Oregon.*

times larger than those which occurred on disturbed sites (10). These results suggest that soil disturbance, vegetation removal, and alteration of drainage patterns create smaller and more localized imbalances in the soil mantle than is common in undisturbed areas. Dyrness felt that some of the larger landslides in clearcut areas might have occurred even if the area had not been logged (10).

Dyrness also found a marked difference in erosion rate between soils from different parent materials; 63.8% of all landslides occurred on soils derived from greenish tuffs and breccias compared with only 6.4% from stony soils from basalt and andesite. Soils from reddish tuffs and breccias ranked between the two at 29.8% (10). Roads were also implicated in more than half of the cases of mass failure in another study of regional scope (41).

Although some disturbance of surface soil results from felling trees and yarding of logs, and burning removes protection provided by vegetation and logging residue, the erosion rate of surface soil does not appear to be excessively large compared to mass erosion. One study showed that most of the soil moved by surface soil erosion came from 80% slopes bare of vegetation and from talus areas following slash burning (28). By the second summer after slash burning, 50% vegetation cover had virtually stopped this surface soil movement. Estimated total annual surface erosion of 3.6 m^3/ha was much less than 21 m^3/ha removed by mass wasting (10).

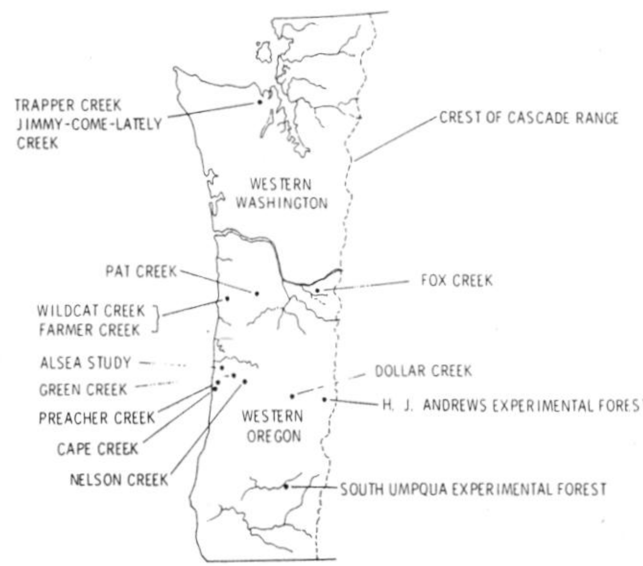

FIGURE 1. Location of experimental watersheds in western Oregon and Washington.

The nature of the site disturbance by the two erosion processes is very different. Landslides usually remove a cross-section of all soil horizons—often including all or part of the underlying parent material—but disturb a relatively small surface area; the converse is true for surface soil erosion. Although data on the area percentage of landslide scars has not been published for Pacific Northwest forests, on similar forested topography in Japan, landslide scars reached a maximum of 1.8% 15 years after clearcutting (22). In the absence of better data, the area of eroding surface soils can be expected to be roughly equivalent to the area of deep soil disturbance (10%) measured on clearcuts harvested by the high-lead cable method in Oregon (9). So apparently the largest volume of soil is moved by landsliding from a relatively small proportion of the forested landscape.

Sedimentation of Streams

Water quality in relation to forest management practices is reported from four watershed experiments currently in progress in western Oregon and Washington (Fig. 1). These are the H. J. Andrews and South Umpqua Experimental Forests, and the Alsea and Fox Creek watershed studies. The effects of clearcutting, forest roads, and logging residue disposal on water quality are demonstrated by the first three watershed experiments listed in Table 1.

Table 1. Characteristics of experimental watersheds in western Oregon.

Watershed	Mean precip. (cm)	Slope (%)	Mean aspect	Timber type	Parent material and soil	Management
Fox Creek	280	7–12	W	Overmature Douglas-fir, western hemlock	Basic igneous glacial till	25% clearcutting and roads with and without slash burning
Alsea[a]	250	35–40	S	Mature Douglas-fir	Micaceous sandstones and mudstones	100% clearcutting vs. 25% clearcutting and roads
H. J. Andrews Experimental Forest[b]	230	53–63	NW	Mature to overmature Douglas-fir	Breccias, tuffs, basalt, and andesites	Clearcutting with and without roads
South Umpqua Experimental Forest	120	18–23	NE	Mature mixed conifer	Breccias, tuffs, and basalt	Roads, shelterwood, clearcutting, and fertilization

[a] Source: (3).
[b] Source: (2, 40).

All three studies were carefully controlled, and the best logging technology available at the time was used on each watershed. Roads were constructed during the summer dry season; therefore construction had only a minimal and temporary effect on water quality. Road surfaces were gravelled, and surface water was controlled by inside ditches and culvert cross drains. Streams were protected, and logging debris removed where it might restrict fish passage or otherwise impair water quality. To lessen damage to soil physical properties, logging residue was burned after fall rains had dampened the surface soil, except at the Alsea study where no rain fell previous to burning. Logs were moved to landings by high-lead or skyline cable methods which cause less soil disturbance than tractor logging (9, 11, 49).

Sedimentation of streams in this region is closely linked to the pulsing action of streamflow caused by fall and winter stormfronts from the Pacific Ocean. Streams rise and fall rapidly in relation to precipitation, storm duration, snowmelt, and amount of water already in the soil. The suspended sediment content of stormflow generally follows the storm hydrograph, and high sediment loads are confined mainly to the storm period (Fig. 2).

At the H. J. Andrews Experimental Forest, soil deposited behind logging residue in the stream channel was released by broadcast burning in the fall of 1966. This raised the general level of stream sedimentation and also the length of time that the stream carried high concentrations (Fig. 2). In fact,

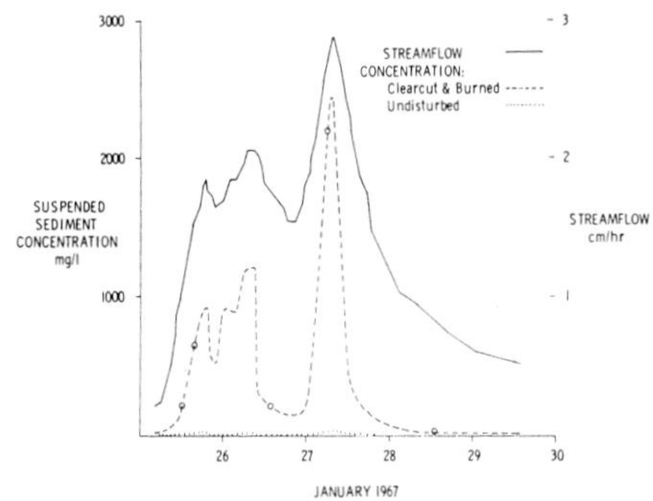

FIGURE 2. Storm hydrograph and suspended sediment trace for the 100% clearcut watershed after broadcast burning and for the same watershed in an undisturbed condition, H. J. Andrews Experimental Forest.

Table 2. Time in days that suspended sediment content of streamflow exceeded given concentration values for the winter season 1966-67, H. J. Andrews Experimental Forest.

Concentration (mg/l)	Number of days per year: Undisturbed	Number of days per year: 100% clearcut, broadcast burned
10	9	96
36	0.12	60
100	—[a]	26
1,000	—	2.4

[a] The maximum measured concentration was 36 mg/l.

the breadth of the sediment-time trace expanded by an order of magnitude at 10 mg/l and more than two orders of magnitude at 36 mg/l—the maximum concentration the stream was estimated to have carried had its contributing watershed been undisturbed (Table 2). Even though a greater sediment concentration extended into the low streamflow periods between winter storms because of clearcutting, the stream contained less than 10 mg/l and was essentially nonturbid for 269 days during 1966-67, the first year after burning. The pulsing of turbid water with periods of winter stormflow is characteristic of all streams in our study areas.

Western Cascade Range

At the *H. J. Andrews Experimental Forest* (Fig. 1), 60 km east of Eugene, Oregon (2), stream sedimentation from an undisturbed watershed was compared with two watersheds: one, 25% clearcut in three patches, and containing 2.7 km of logging road (6% of the watershed area), and the other entirely clearcut and containing no roads (16). Logging residue was burned following the completion of yarding, and road cutbanks and fill slopes were initially stabilized by the application of grass seed, mulch, and fertilizer. The mean annual and mean maximum concentration of suspended sediment in the streams of the logged watersheds and the control are summarized in Table 3. The mean annual values for each watershed after timber harvest are compared with that for the control stream in Fig. 3A.

Increases in stream sediment concentration after timber harvesting were closely related to the kinds of soil mantle disturbances caused by the roads and clearcuts and soil instability on steep slopes caused by the removal of forest vegetation. The greatest impact on water quality occurred when soil deposited in stream channels by landslides became high velocity debris torrents composed of soil, gravel, boulders, and organic debris which passed through the stream channel (16). One of these events which originated from a

road fill slope in 1962 (Fig. 3A), raised the mean annual concentration to 261 mg/l vs. 4mg/l for the undisturbed stream; comparable mean maximum concentration values exceeded 6,300 mg/l vs. 122 mg/l from the undisturbed stream (Table 3). Again, after an unusually severe storm event in 1965, landsliding associated mainly with roads raised the mean maximum and mean annual concentration values to even greater levels. The soil removed by these periods of landsliding exposed subsoils next to streams and deposited soil in the lower portions of the channel. Erosion from these sources during the years following each event (1963-64 and 1966–68) supplied the stream with greater concentrations of suspended sediment than came from the surface erosion and sediment transported from the road cut and fill slopes measured in 1960 and 1961. The effect of clearcutting and slash burning in 1963 did not noticeably interrupt the stabilizing trend in 1963-64 following the landslide of 1962 (Fig. 3A), indicating that these practices contributed only small quantities of soil to the stream compared to landslides coming mainly from the roads.

The effect of clearcutting alone is also shown in Fig. 3A. Logging of this entire drainage was done from 1962 through 1966. When clearcutting was 30 and 74% completed in 1963 and 1964, respectively, the mean annual and maximum concentration of suspended sediment was not significantly different from the concentration we would have estimated for the undisturbed

Table 3. Mean maximum and mean annual concentration of suspended sediment in streams from watersheds that were undisturbed, 25% clearcut with roads, and 100% clearcut without roads, H. J. Andrews Experimental Forest.

Year	100% clearcut without roads: Mean maximum		100% clearcut without roads: Mean annual	Undisturbed: Mean maximum		Undisturbed: Mean annual	25% clearcut plus roads: Mean maximum		25% clearcut plus roads: Mean annual
	mg/l								
1957	290		8.6	330		6.3	182.	a	10.1
1958	230		13.2	330		11.8	230		21.8
1959	29		2.3	45		2.2	42		3.8
1960	10	a	1.6	16		1.4	110	b	10.3
1961	108		6.5	200		5.5	370		22.7
1962	124		6.0	122		4.0	> 6,300		261.0
1963	14	c	1.5	28		1.6	700	c, d	14.4
1964	14		1.4	16		1.3	700	e	13.1
1965	4,400		74.4	2,100		44.6	> 15,000		2,470.0
1966	470		18.7	28	a	1.6	780		33.1
1967	2,000	d	121.0	28		1.5	750		29.8
1968	2,600	e	68.4	28		2.0	870		21.7

a. Undisturbed.
b. Roads only.
c. Clearcutting.
d. Slash burning.
e. Revegetating.

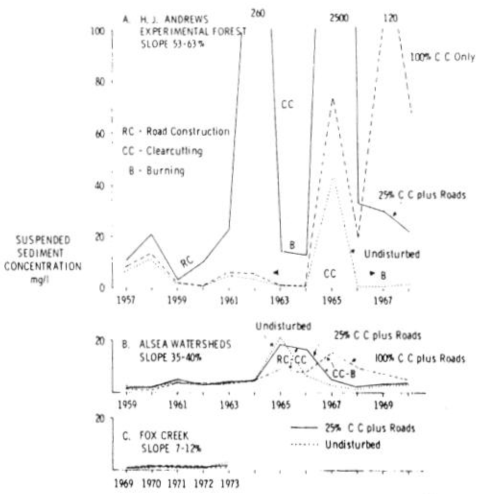

FIGURE 3. Mean annual suspended sediment concentration of roaded, clearcut, or undisturbed streams from three experimental watersheds studies: *A.* H. J. Andrews Experimental Forest—complete clearcutting without roads and 25% clearcut plus roads (16); *B.* Alsea watersheds—Deer Creek, 25% clearcut plus roads, and Needle Branch entirely clearcut plus roads (4); *C.* Fox Creek—both watersheds 25% clearcut plus roads and logging residue disposal by broadcast burning or decomposition by natural means.

stream (Table 3).[2] The low concentration was undoubtedly due to the filtering effect of large quantities of logging debris which then filled the stream channel. In 1965, about 600 m^3 of soil from landslide erosion entered the stream of this small drainage, but most was trapped behind the logging debris in the stream channel. However, the small amount of soil that was carried downstream during high flows raised the mean annual suspended sediment concentration significantly in 1965 and 1966. The slash fire in October, 1966, consumed much of the logging debris in the stream channel and, as a result, the soil was released. The greatest mean annual concentration came from clearcutting in 1967, the first season after slash burning, when the stream cut through the soil previously deposited in the stream channel from landslides in 1965. Soil surface erosion on the hill slopes was also most active at this time (28). But a higher maximum concentration was noted due to landsliding in 1965 (4,400 mg/l) than was measured in 1967 and in 1968 after burning (2,000 and 2,600 mg/l, Table 3). The partial stabilization of the channel and removal of fine sediment is evidenced by the lower concentration of suspended sediment during the following year (1968).

[2] *Significance refers to the 95-percent probability level in this paper.*

At least three sources of soil could have contributed to the increased sedimentation in the clearcut watershed in 1967 and 1968: erosion of (a) soil deposited and trapped behind logging debris in the stream channel in 1965, (b) erosion of subsoils exposed by landslides, and (c) erosion of surface soil exposed or physically altered by slash burning. Of these sources, the 0.06 cm of soil deposited in the stream channel in 1965 was the most readily available and primary source for the 0.038 cm of soil lost from the watershed in 1967 and 1968; the stream cut through this material leaving terraces on either side during this period. Soil erosion from side slopes (0.036 cm) was nearly equal to soil loss from the entire watershed, but much of this soil was trapped by stumps and logs and therefore did not reach the stream channel (28).

In summary, increased erosion from roads caused the most serious impairment of water quality in this study, and landslides from these roads were the predominant means for delivery of the soil to the streams (Fig. 3A, 1962 and 1965). Clearcutting exclusive of forest roads was next in importance where landslides from clearcut areas entered streams (Fig. 3A, 1965–68); in the absence of landsliding, clearcut areas contributed little or no soil (fig. 3A, 1963-64). Erosion of subsoils from landslides (Fig. 3A, 1963-64 and 1966–68) was greater than surface soil erosion from roads (Fig. 3A, 1960-61). The effect of burning on the delivery of soil to the study streams was undoubtedly very small from both watersheds; the mobilization of soil from the stream channel of the clearcut watershed can be considered a special case where soil from landslide erosion is temporarily retained within the channel instead of being removed at the time of deposition by torrent flows.

Table 4. Mean 3-week maximum and mean annual concentration of suspended sediment in streams from watersheds that were undisturbed, 25% clearcut and burned, and 25% clearcut with residues left to decompose, Fox Creek watershed.

	25% clearcut and burned		Control		25% clearcut and not burned	
Year	Mean maximum	Mean annual	Mean maximum	Mean annual	Mean maximum	Mean annual
	mg/l					
1969 e	1.1 b	.7	1.5	.6	1.3 a	.7
1970	2.8 c	.8	4.5	.7	4.1 b	1.4
1971	4.3 d	1.3	3.6 a	.7	4.3	.8
1972	4.0	1.1	1.4	.6	2.1	.7
1973 f	3.2	1.0	7.3	2.4	5.8 d	1.9

a. Undisturbed.
b. Clearcutting.
c. Slash burning.
d. Revegetating.
e. May 1-Sept. 30, 1969, only.
f. Oct. 1, 1972-Mar. 29, 1973, only.

Since 1968, soil erosion has continued in both logged watersheds because of continued landsliding. Consequently suspended sediment concentrations have remained elevated relative to the control stream.

The *Fox Creek watersheds* (Fig. 1) are tributaries of the Bull Run River—the domestic water supply for Portland, Oregon (Table 1). Timber harvesting of the experimental watersheds followed the guidelines specified by the U.S. Forest Service and the City of Portland Water Bureau. Trees were felled and logs removed so that streams were not disturbed.

No increase in the sedimentation of these streams has been observed (Fig. 3C and Table 4). Because of the gentle topography and stable soils, the only increase in sediment concentration came at the time that road culverts were placed in the streams, and the effect of this disturbance lasted for a few hours and could be traced only a short distance downstream (29).

Oregon Coast Ranges

The *Alsea watersheds* (Fig. 1), tributaries of Drift Creek, in the Oregon Coast Ranges, were harvested like those at the H. J. Andrews Experimental Forest (Table 1). The topography here is less steep and the forest roads were located along ridgetops to avoid crossing small, steeply incised tributary drainages. The climate is more moderate than at the H. J. Andrews watersheds due to the moderating influence of the Pacific Ocean and ample precipitation; also, the growing season is longer.

Table 5 compares the maximum mean daily and mean annual concentration of suspended sediment of Needle Branch drainage (entirely clearcut) and Deer Creek watershed (25% clearcut in three blocks) with Flynn Creek—the control stream. Fig. 3B shows a more detailed comparison of the water quality in each watershed.

The greatest water quality change occurred in the Needle Branch watershed stream following complete clearcutting and slash burning (Fig. 3B). The mean suspended sediment concentration of the stream increased significantly in 1966 due to road drainage and sidecast soil from newly constructed roads (4). The largest increase (also significant) came after slash burning in 1967 and was apparently due to increased surface soil erosion after an extremely hot slash fire; both the mean and mean daily maximum concentrations remained elevated (statistically significant) with respect to the control through 1969 (Table 5). Revegetation of this clearcut was very rapid, and, by 1970 (three years after burning), the mean annual and maximum sediment concentrations (4.4 and 238 mg/l, respectively) were not significantly different from the control stream (2.9 and 223 mg/l, respectively).

Sedimentation of Deer Creek was increased in 1966 due to a single landslide which originated from one of the roads (Fig. 3B) (4). Neither clearcutting nor slash burning of two of the three clearcut units significantly increased the suspended sediment concentration of Deer Creek.

Table 5. Mean daily maximum and mean annual concentration of suspended sediment after 100% clearcutting of Needle Branch, 25% clearcutting of Deer Creek, and no cutting in Flynn Creek watershed.[a]

Year	Needle Branch: Mean daily maximum		Needle Branch: Mean annual	Flynn Creek - Control: Mean daily maximum		Flynn Creek - Control: Mean annual	Deer Creek: Mean daily maximum		Deer Creek: Mean annual
	mg/l								
1959	72	a	1.2	82		2.1	104		1.8
1960	100		0.9	95		1.4	130		1.6
1961	220		3.8	365		4.6	359		5.0
1962	249		3.6	190		2.3	209	a	2.5
1963	140		3.7	220		3.4	264		4.2
1964	150		4.5	350	a	4.5	234		4.2
1965	300		9.3	1,580		21.4	1,220		18.2
1966	477	b	7.9	390		6.6	1,010	b	16.3
1967	802	c, d	15.8	219		2.7	327	c, d	4.4
1968	1,260	e	10.3	97		1.5	143	e	2.0
1969	338		7.9	170		2.6	197		3.1
1970	238		4.4	223		2.9	212		3.8

[a] Mean annual concentration computed from annual runoff (47) and annual suspended sediment discharge (48). Maximum daily concentration taken from (48).
a. Undisturbed.
b. Road construction.
c. Clearcutting.
d. Slash burning.
e. Revegetating.

Evaluation of data from the Alsea watershed study shows that the largest increase in suspended sediment concentration apparently came from broadcast burning. Although landsliding caused a nearly equivalent increase, the effects of the landslide did not persist beyond one year.

Interrelations of Logging Practices, Soil Stability, and Stream Sedimentation

Increasing sedimentation of streams from logging can be expected as the inherent soil stability decreases and disturbance of soil and vegetation increases. Studies in small drainages in Oregon have shown that sedimentation of streams from both undisturbed and logged watersheds increases as hill slopes steepen, but the effect is amplified in logged areas (Fig. 4). In the western Cascades (Fig. 4), the spread between sedimentation levels was greatest on the steepest slopes (53–63%) and was undoubtedly heightened due to a severe storm midway in the harvest phase. Additional sedimentation on this site was also caused by the construction of roads across the steep drainage headwall and first-order stream channels. The spread of sedimentation levels was much narrower at Needle Branch—the site of intermediate steepness (35–40%). The mean 1966–70 suspended sediment concentration of

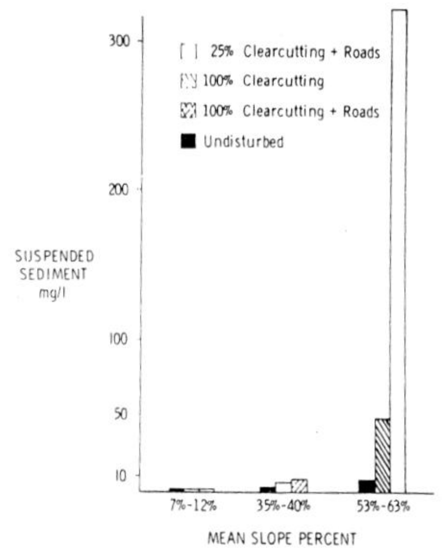

FIGURE 4. Effects of land slope and attendant soil instability on the mean annual suspended sediment concentrations of streams from varying levels of timber harvest and forest road densities at Fox Creek (7 to 12% slope), Alsea (35 to 40% slope), and H. J. Andrews (53 to 63% slope).

9.3 mg/l that resulted from roads, complete clearcutting, and slash burning at Needle Branch watershed in the Oregon Coast Range was only slightly greater than the sedimentation of the undisturbed stream (8.5 mg/l) at the H. J. Andrews Experimental Forest in the western Cascade Range. This figure emphasizes that the greatest care and ingenuity must be exercised in the harvest of forests from steep slopes if unacceptable levels of stream sedimentation are to be avoided.

Chemicals in Forest Streams

There is much current interest in the loss of native nutrients and in introduced chemicals from managed forests and the effect of these chemicals on streamwater quality. The relevant questions are: (a) do concentrations of chemicals increase in streams after management practices are applied? (b) are these concentrations toxic to living organisms? (c) are increased chemical concentrations in streams or losses from the land important to productivity in streams or forest sites?

Native Nutrients

Undisturbed Forests. Nutrients are retained and used very efficiently by Douglas-fir forests. Cations returned in litterfall are efficiently held in the forest floor or surface soil and slowly released to tree roots (7). Much larger cation losses can be attributed to mineral weathering below the root zone than from the loss of litter-supplied cations (18). Nitrogen losses are small and occur predominantly as dissolved organic matter or soil suspended in streamflow (17). Nitrate-N concentrations in streamflow from these undisturbed Douglas-fir forests average 0.002 mg/l, and the annual loss of this ion has been measured at 0.004 kg/ha (18). Concentrations of P in streamwater range up to 0.05 mg/l, with about half in the form of dissolved organic matter and the remainder as inorganic P. Nitrogen and P will be emphasized in the following discussion because of their limited supply in soils and streamwater, and the potential for increased primary production in streams after logging.

After Clearcutting. The N and P concentrations in forest streams increase following clearcutting for several reasons. Uptake by vegetation is virtually stopped. An abundance of plant tissue (logging residues) becomes detritus and subject to decomposition. A warmer and more moist microclimate aids decomposition of organic matter by microorganisms. Soil erosion rates are often increased (17, 25).

The influence of nutrient uptake on soil N mobilization and loss in streamflow has been demonstrated by a series of experimental watershed studies in New Hampshire. These studies compare stream NO_3 responses to forest clearing with and without the normal uptake of N by the growth of hardwood sprouts. The stream concentration of NO_3 was roughly three times greater where revegetation was prevented by the application of herbicides (25) than where normal resprouting was allowed (39). Presumably uptake by stump sprouts had immobilized the N and reduced the leaching loss of NO_3.

Following clearcut logging, there is a rapid expansion of soil invertebrate fauna and of fungal and bacterial decomposer populations due to changes in soil environment. Moisture stress is reduced, and soil-water storage is ample because of reduced transpiration rates. The activity of soil microbes is also favored by increased temperature near the soil surface. Large quantities of logging residue (8) and dead roots furnish ready supplies of energy and nutrients for these organisms—especially in the early years after clearcutting. These conditions favor the rapid disappearance of the finely divided organic fraction and the release of nutrients. Changes in microclimate may be particularly important to nutrient mobilization where thick forest floor accumulations are present from the preexisting forest. Such is the case in the White Mountains of New Hampshire where NO_3 concentration in stream water reached a very high concentration, presumably from decomposition of forest floor and residue from clearfelling (39). In the Pacific Northwest, where the soil is moist and temperature is adequate for decomposition from fall through spring, forest floors are thin and there is less carryover of nutrient capital of the preexisting undisturbed forest to clearcut areas (19).

Stream Nutrient Concentrations After Timber Harvest. Complete clearcutting increased the N and P concentration of streamflow at two experimental watershed studies in western Oregon. At the H. J. Andrews Experimental Forest, moderate increases of NO_3-N at the completion of clearcutting in 1966 were raised to a maximum concentration of 0.6 mg/l in 1968, one year after slash burning (Table 6)—much lower than the permissible limit of 10 mg/l (14). Both NH_3-N and Mn concentrations in streamflow exceeded permissible limits for a period of 12 days after the slash fire but quickly declined to undetectable levels (17). By 1972, the mean NO_3 concentration dropped to 12% of the mean measured in 1968; this drop was associated with the rapid revegetation of the clearcut and the progressive increase in the proportion of evergreen shrub cover (Fig. 5), which is capable of photosynthesis and nutrient uptake any time of the year when sunlight and air temperature permit. The inorganic P concentration of both streams was similar following clearcutting, but before burning, in 1966 (Table 6). Increased concentrations were evident the first year after slash burning (1967). A progressive decline in the mean and the maximum was measured in 1971 and 1972. However, interpretation of the results is made difficult by the erratic concentration of inorganic P in the control stream.

At the Alsea watershed study in the Oregon Coast Ranges, the maximum NO_3 concentration in Needle Branch watershed after clearcutting and slash

Table 6. Mean annual and instantaneous maximum concentrations of nitrate and phosphorus dissolved in streamflow from clearcut and control watersheds, H. J. Andrews Experimental Forest. Logging debris was burned on the clearcut watershed to reduce fire hazard.

	Nitrate - N			Orthophosphate - P		
	Clearcut		Control	Clearcut		Control
Year	Maximum	Mean	Mean	Maximum	Mean	Mean
	mg/l					
1966	.050	.020	.010	.066	.024	.026
1967[a]	.066	.050[b]	.003	.121	.039	.016
1968	.600	.200	.001	[c]	[c]	[c]
1971	.065	.046	.0003	.050	.036	.032
1972	.056	.023	.0015	.045	.034	.016

[a] Following slash burning.
[b] In addition to the nitrate, .11 mg/l of ammonia nitrogen.
[c] Data not available.
Source: 1966–68 (17); 1971-72, unpublished data.

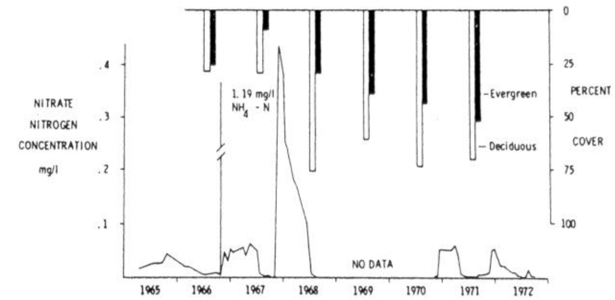

FIGURE 5. Mean biweekly nitrate and ammonia concentration in streamflow and percent vegetation cover following clearcutting and slash burning at the H. J. Andrews Experimental Forest, Blue River, Oregon (17).

burning increased to 2.1 mg/l (5). This was three and a half times greater than the maximum observed at the H.J. Andrews Experimental Forest, but well below concentration levels important for human health (14). The mean annual NO_3 concentrations were 0.44 mg/l in 1967 and 0.43 mg/l in 1968, the first two years after treatment, compared with concentrations of 0.12 and 0.19 mg/l in 1965 and 1966 before logging. By 1971, the peak NO_3 concentration was 0.3 mg/l, or about equal to the lowest concentration observed before clearcutting. No NO_3 concentration increase was observed in the 25%-clearcut Deer Creek, and an increased P concentration was not observed in either watershed.

Nitrate concentration at Fox Creek (Table 7) followed a cyclic pattern similar to that observed at the H. J. Andrews Experimental Forest. The mean concentration (0.012 mg/l) after 25% clearcutting and burning was only slightly higher than the concentration measured in the control watershed (0.006 mg/l) during the spring and summer of 1970 (Table 7). The maximum concentration (0.079 mg/l) came in December, 1970, two months after slash burning. The mean NO_3 concentration peaked at 0.46 mg/l during the second year after slash burning. A similar delay period was observed at the H. J. Andrews Experimental Forest, but both the mean and maximum concentration values for Fox Creek were lower, even if adjustments are made for the proportion of the total area clearcut.

At the South Umpqua Experimental Forest in southwestern Oregon (Table 1 and Fig. 1), stream effects of clearcut and shelterwood logging are being compared. In order to reduce fire hazard, logs were yarded and piled on landings from both logging treatments. Water sampling began in 1969—two years before timber harvest and one year before the construction of logging roads.

Nitrate concentrations for 1969 and 1970 and the first half of 1971 were low and are not shown in Fig. 6. After the completion of logging in the shelterwood-cut watershed in late September 1971, slight increases of NO_3 concentration were noted through 1972. The rapid rise in NO_3 concentration evident during the winter of 1972-73 followed one year after the completion of clearcutting. The cause of the NO_3 concentration rise in the control watershed in unknown, but may be due to leakage from the adjacent clearcut watershed.

Similarities in the NO_3 concentration cycle are evident for all four experimental watershed sites in western Oregon. Nitrate concentration in streamflow is closely related to soil hydrology. The maximum NO_3 concentration is often measured early in the winter after the soil water-storage capacity is exceeded by fall rains (Fig. 5). Minima come in the dry summer months when matric tension of soil does not permit entry of soil solution to streams, and active biological communities in streams are sinks for nutrients entering in seepage flow. From this evidence, we have formed the hypothesis that NO_3 accumulates in soils on clearcuts during spring and summer months. The maximum stream concentrations of NO_3 in early winter may correspond to the peak concentrations in soil solution during the fall months. The NO_3 concentration is undoubtedly augmented by decomposition and microbial transformations through the winter period.

Decline of NO_3 concentration in streamwater in the years after cutting is likely the result of dwindling supplies of readily decomposable organic matter (logging residue) and the increasing uptake and retention of nutrients by rapid vegetation growth. Where revegetation is most rapid, as on the Oregon coast, the period of increased NO_3 outflow from clearcutting may not persist into the sixth year. Where revegetation is somewhat slower at the H. J. Andrews Experimental Forest, it was five years after slash burning before NO_3 in streamflow declined to less than one-quarter of the maximum concentration measured after burning.

Table 7. Mean annual and 3-week maximum concentration of nitrate-N in streamflow from clearcut and burned and control watersheds at Fox Creek in the Bull Run Watershed near Portland, Oregon[a]

	25% clearcut		Control
Year	Mean maximum	Mean	Mean
	mg/l		
1970[b]	.019	.012	.006
1971	.079	.027	.003
1972	.056	.046	.005
1973	.043	[c]	[c]

[a] Mean annual concentration summarized from the previous Oct. 1 to Sept. 30 of the year indicated.
[b] Analysis period from Apr. 22–Sept. 30, 1970.
[c] Data not available.

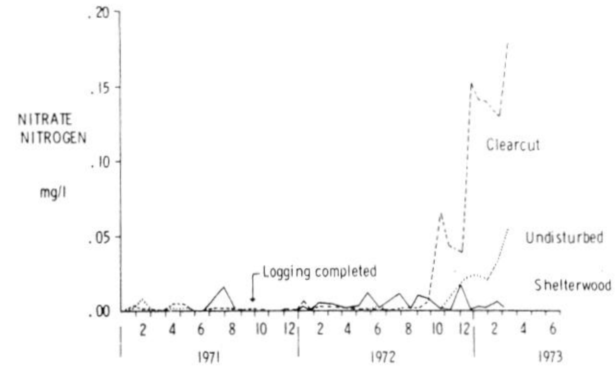

FIGURE 6. Mean three-week nitrate concentration in streamflow from entirely clearcut, shelterwood-cut, and undisturbed watersheds at the South Umpqua Experimental Forest. Timber harvesting was completed the summer of 1971.

The small rise in inorganic P concentration noted after logging at the H. J. Andrews Experimental Forest contrasts with the Alsea study where no increase in P concentration was measured. It is too early to draw conclusions at Fox Creek and the South Umpqua Experimental Forest.

Forest Fertilizers and Herbicides

Increasing demand for wood products from a decreasing production base has resulted in an acceleration of intensified management practices on forest lands. In order to increase timber production and at the same time meet increasing demands for forage, water, wildlife, and recreation, the forest land manager has turned to the use of chemical tools. In the following sections, we will consider the mechanisms of entry and the fate of aerially applied fertilizers and herbicides in forest streams.

Fertilizers. Operational forest fertilization began in the Douglas-fir region of the Pacific Northwest in 1965 when Crown Zellerbach Corporation fertilized 607 ha in western Oregon. The practice has grown rapidly as a result of advances in fertilizer technology, improved application methods, and more favorable economic conditions. Approximately 150,000 ha are being fertilized each year (21).

Nitrogen is the most common growth-limiting element in this region, and all of the major coniferous commercial timber types have responded to N fertilization (20). Growth response has not been influenced by form of N, and granular urea (46% N) has been used almost exclusively. This N fertilizer is a high analysis source well adapted to aerial application in addition to being available in adequate quantities. Application rates vary with site and timber type, but are usually 370 or 493 kg urea/ha (150 or 200 lb N/acre).

Nitrogen fertilizer is applied to forested watersheds in the Douglas-fir region by helicopter. Nearly all of the fertilizer applied reaches the intended target, but uniform application is hampered by irregularly shaped units, uneven topography, and obscure boundaries. Actual application rates at any given point within the unit may vary by as much as 20 to 60% (43).

Initial distribution of aerially applied fertilizers is limited to the forest floor and surface water compartments of the forest. Drift problems due to dust have been largely eliminated by the introduction of large, specially coated urea granules (forest grade urea), and very little granular fertilizer is intercepted by a dry forest canopy. Thus, the amount of fertilizer N entering forest streams by direct application can be minimized by carefully marking and avoiding larger streams during application. However, most applicators find it impractical to avoid small headwater streams. The size of stream which should be avoided to prevent excessive contamination has not been established.

Fertilizer N can enter forest streams after application as a result of surface runoff or in subsurface drainage. However, because of the high infiltration rates characteristic of most forest soils of this region, surface runoff rarely occurs. Forest soils are excellent filters for most soluble plant nutrients because of their high exchange capacities and the presence of dense root systems which can absorb and recycle nutrients. Some leakage from the soil system does occur, however, and measurable levels of NH_4-, NO_3-, urea-, and soluble organic-N are found in several streams being monitored for water quality in western Oregon and Washington.

Nitrogen in streams has been measured in connection with several operational forest fertilization projects in the Pacific Northwest over the past four years (6, 26, 27, 30, 35, 45). In each study, water samples have been collected from streams flowing through or adjacent to fertilized units (a) before treatment to establish background levels, (b) during treatment, and (c) for varying lengths of time after fertilization. Sampling intensity has not been uniform and analyses have been conducted in several different laboratories. However, the results show very similar patterns regardless of location, size of area fertilized, or size of stream sampled.

A 68-ha experimental watershed in southwestern Oregon was fertilized with 224 kg urea-N/ha in March 1970 (Fig. 7A) (31). Urea concentrations increased slowly and reached a maximum of 1.39 ppm urea-N 48 hours after application started. Ammonia-N reached a peak concentration of 0.044 ppm in the same time interval. Nitrate-N began to increase the second day after

application and peaked at 0.168 ppm in 72 hours. Nitrite-N was not detected. Higher peak concentrations have been reached in other studies during the first few days after treatment, but levels detrimental to human health have not been reported for any form of N. Concentrations of urea-N may reach relatively high levels as a result of excessive direct application to stream channels, but these peaks usually do not persist for more than a few hours. Within three to four days, levels of urea-N return to nearly pretreatment concentrations. Measurable increases in NH_3-N are found only when fertilizer N is directly applied to the stream.

All loss of applied N after the first three to six weeks occurred as NO_3. Within two months after fertilization, NO_3-N concentrations returned to pretreatment levels (Fig. 7B). Little or no loss of fertilizer N occurred during the dry summer months. However, with the beginning of fall rains, NO_3-N concentrations reached a second peak. Both streamflow and NO_3-N levels remained high through December and January in the Coyote Creek study, and 92% of the total amount of fertilizer N lost during the first year (0.38 kg N/ha) was lost between November 11, 1970, and February 3, 1971.

Similar patterns of N levels in streams have been measured in other studies. In every study where sampling has continued long enough after fertilization, a second peak of NO_3-N has been detected. However, the NO_3-N level usually returns to background concentrations within three to six weeks.

The impact of forest fertilization projects on streamwater quality has been monitored over a wide range of soil types and ages and densities of overstory and understory vegetation. Studies summarized in Table 8 are representative of most of the stand types in the Douglas-fir region that are likely to be fertilized. Peak concentrations of various soluble forms of N found in streams after fertilization do not approach toxic levels. Usually less than

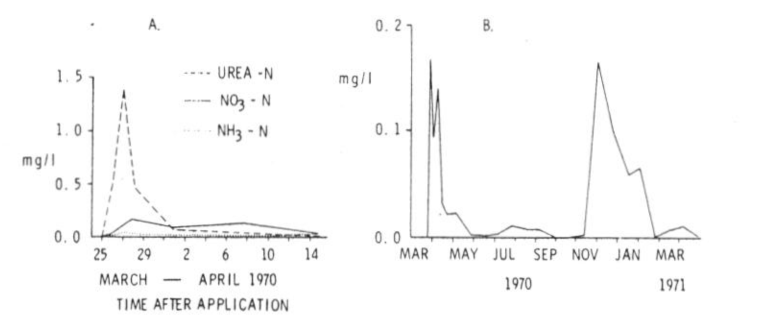

FIGURE 7. Fertilization of a 68-ha watershed with 224 kg urea-N/ha in March 1970: *A*. Immediate effect on water quality; *B*. Effect on NO_3-N concentration in streamflow for 1 year following fertilization.

Table 8. Characteristics of representative forest-fertilization, water-quality study sites, pretreatment levels, and peak concentrations of urea-, ammonia-, and nitrate-nitrogen found in western Oregon and Washington streams following early spring fertilization.

Location	Stand type and age	Area treated[a] (ha)	Percent of watershed treated	Mean annual rainfall (cm)	Mean pretreatment concentration (mg/l)			Peak post-treatment concentration (mg/l)		
					Urea-N	NH_3-N	NO_3-N	Urea-N	NH_3-N	NO_3-N
Coyote Creek, Umpqua NF	Mixed conifers, old growth	68	100	120	.006	.005	.002	1.390	.048	.177
Trapper Creek, Olympic NF	Douglas-fir, 40 years	64	< 10	102	.008	0	.034	.700	.010	.121
Jimmy-come-lately Creek, Olympic NF	Douglas fir, 10 years,	49	< 10	115	.002	0	.005	.708	.040	.042
Nelson Creek,[b] Siuslaw drainage	Douglas fir, young growth	38	100	153	< .02	.01	.290	8.60	.32	2.10
Dollar Creek,[b] McKenzie drainage	Douglas-fir, young growth	34	100	140	< .02	.03	.060	44.40	.49	.13
Pat Creek, Yamhill drainage	Douglas-fir, 35 years	243	63	190	.003	.007	.070	3.26	.034	.388

[a] All units were fertilized with urea at 224 kg N/ha in March or April of 1970, 1971, or 1972.
[b] Source: (6).

0.5% of the applied N enters stream channels. Peak concentrations are associated with direct application to the surface water and adjacent riparian zone of larger streams flowing through the treated area. Data from several studies show low initial concentrations of urea-N and NH_3-N when direct application to surface waters is intentionally avoided.

Herbicides. Douglas-fir is unable to compete effectively with most brush species for light, water, and nutrients during the early stages of stand development. Herbicides are effective tools to minimize competition by brush. 2,4-D, 2,4,5-T, amitrole, and to a lesser degree, picloram and dicamba are used in the Douglas-fir region to aid in establishment and development of young conifer stands. In 1972, more than 13,000 ha of Forest Service land in Oregon and Washington were treated with herbicides for site preparation prior to planting and for release of established conifers from brush competition. On private forest lands, more than 14,000 ha were treated for site preparation alone. Herbicides are used to desiccate established brushfields for burning, reduce brush density, increase survival of planted stock, and release established plantations from excessive brush competition. Applications are usually made by helicopter from March through October. The specific chemical or combination of chemicals used, formulation, and rate and timing of application vary with the species to be controlled, the purpose of the application, the season, and the stage of stand development. Precommercial thinning operations, where concentrated herbicide formulations are injected into individual tree stems, are not likely to introduce significant herbicide residues into streams.

Aerially applied herbicides are initially distributed to the air, vegetation, forest floor, and surface water of the forest. The amount of chemical entering each of these will be determined by the chemical and application techniques used and environmental conditions. This initial distribution largely determines the amount of herbicide which will ultimately enter forest streams.

Herbicides can enter forest streams in drift or direct application of spray materials to surface waters, in overland flow with surface water runoff, or in subsurface water flow through the soil. The magnitude and duration of stream contamination is markedly different for each of these processes (Table 9).

Several studies of herbicide residues in Northwest forest streams have been conducted in connection with the operational application of brush control chemicals. The results have been surprisingly consistent despite differences in the chemicals used, seasons of applications, and nature of the area treated (Table 10).

Some herbicide was found in most streams which flowed through or by treated areas shortly after application. Peak concentrations occurred shortly after application, but residues usually did not persist for more than a few

Table 9. Magnitude and duration of herbicide entry into forest streams.

Mechanism of entry	Magnitude of peak residues (mg/l)	Duration of entry
Drift or direct application to stream surface	> 0.01	hours
Overland flow	< 0.01	days
Leaching and subsurface flow	< 0.001	weeks

days. This type of contamination is a result of drift or direct application to surface waters and can largely be avoided by exclusion of streams from treatment areas and carefully controlled application techniques. Forest managers have an obligation to minimize the entry of chemicals to nontarget areas.

Stream contamination from overland or subsurface flow might occur during periods of heavy precipitation some time after herbicide application. However, herbicide residues were not detected in samples collected several months after herbicide application at the study sites in Table 10. At two other locations, samples were collected in connection with first fall storms six months after application of 1.12 kg/ha each of 2,4-D and 2,4,5-T (33). Approximately 193 ha (6%) of the Cape Creek watershed was treated with 2, 4-D and 2,4,5-T. One spray unit containing 171 ha was adjacent to the stream for 3.7 km and extended 200 to 500 m upslope. In the Green Creek watershed, 165 ha in 25 separate units (14% of the watershed) were treated. Five water samples each were collected at Cape and Green Creeks over a 12-day period during the first major storm of the fall. Rainfall was 9.35 cm (3.00 cm on day 6) at Cape Creek and 10.70 cm (7.92 cm on day 5) at Green Creek. Both Cape and Green Creeks offered good opportunity to detect herbicide runoff, but measurable residues were not found (33).

We have not found a single instance where herbicide residues were detected in Northwest forest streams more than one month after application in more than eight years of monitoring. In most cases, all residues were gone in a few days. We conclude, therefore, that leaching and overland flow of herbicides from these forest lands probably does not occur to any significant degree.

Some herbicides may occur in streams during and shortly after application. The impact of these residues on aquatic organisms depends on both the magnitude and duration of their exposure. Maximum herbicide concentrations in excess of 0.05 mg/l should not occur when direct application to the stream surface is avoided. Average concentrations over the first 24 hours after application are unlikely to exceed 0.01 mg/l. Most aquatic organisms

Table 10. Herbicide residues in Northwest streams.

Preacher Creek[a]			Wildcat Creek[b]		Farmer Creek[c]	
Time (hr)	2,4,5-T (mg/l)	2,4-D (mg/l)	Time (hr)	Amitrole (mg/l)	Time (hr)	Dicamba (mg/l)
.05	.012	.006	.05	0	.6	0
.75	.004	.004	.33	0	1.7	0
1.75	.006	.013	.67	.009	2.1	.001
5.5	.002	.004	1.07	.090	2.7	0
16.4	.001	.001	1.38	.110	3.3	.003
18.8	.001	.002	1.6	.040	3.8	.012
22.5	.003	.005	2.0	.035	4.3	.016
27.3	.001	.002	2.8	.024	4.8	.028
39.4	.001	.001	4.2	.014	5.3	.037
46.0	0	0	5.2	.007	6.2	.033
12 samples from 46 hours to 9 months postspray	0	0	6.9	.005	6.8	.030
			10.3	.003	7.8	.027
			15.2	.002	8.8	.024
			20.5	.025	10.2	.016
			26.0	.008	13.1	.011
			69.4	0	28.8	.006
					30.1	.002
					50.2	0
					96	.004
			7 samples from 72 hours to 36 days postspray	0	144	.009
					216	0
					20 samples from 263 hours to 14 months postspray	0

[a] 1.12 kg/ha each 2,4-D and 2,4,5-T low volatile esters in diesel oil. Helicopter application in March (Norris, L. A., M. Newton, and J. Zavitkovski, Oregon State University, Corvallis, unpublished data).
[b] 2.24 kg/ha amitrole as amitrole-T in water. Helicopter application in July (32).
[c] 1.12 kg/ha dicamba in water. Helicopter application in June (36).

can tolerate this degree of exposure with little or no effect. Careful application of herbicides will pose minimum hazards to aquatic organisms (35, 46).

Herbicide reaching the surface of the forest floor will enter the floor and soil profile with precipitation. Organic matter is the single most important soil characteristic which influences adsorption and leaching of herbicides in soil (1). The high organic matter content of Pacific Northwest forest soils favors extensive herbicide adsorption and, therefore, limited leaching.

Degradation is the only means by which the total environmental load of an herbicide is reduced. Biological degradation of herbicides predominates, but chemical degradation is important for some (24). There are marked differences among the rates of degradation of various herbicides in forest floor material, but most of the commonly used herbicides will not persist in significant quantities for more than one growing season (34).

Forest managers can minimize the potentially adverse environmental impacts of forest spraying by maximizing the placement of spray materials in the target area where chemicals not acting on target organisms can enter the forest floor and soil. We view the forest floor and soil as a superb environment for minimizing the potential impact of herbicides on forest streams. High infiltration capacities prevent overland flow. Adsorption phenomena retard chemical movement through the soil, and chemical and biological processes alter the material to innocuous substances.

Discussion

In general, landslide erosion is the predominant means of slope retreat in the Cascade and Coast Ranges of the Pacific Northwest. In the steepest undisturbed experimental watersheds reported here, stream bank erosion was the predominant source of stream sedimentation. Mass wasting of soil was retarded or prevented by the forest cover and anchoring effect of tree roots. Stream sedimentation is commonly raised by winter storms to peak concentrations of 200 to 300 mg/l; these streams carried more than 10 mg/l for one to three days per year depending upon the number and intensity of storm events (40).

Timber harvest may increase stream sedimentation depending upon the potential for landsliding as indicated by angle of slope and according to the logging-caused soil disturbance. Landsliding from forest roads has been the single most important source of increased stream sedimentation. At the steepest site (H. J. Andrews Experimental Forest), erosion of road fills and soil cast aside where truck roads crossed steeply inclined tributary stream channels raised stream sedimentation to 46 times that of the control stream. The spread between stream sedimentation response to the logging treatments may have been amplified by a runoff event in 1965—with an expected return period of 50 to 100 years—three years after clearcutting began at the steepest site. The much smaller increase at the Alsea watersheds (intermediate steepness) may have resulted from more conservative road location, more stable soils, and also because logging came one year after the extreme storm event of 1965. In spite of these difficulties, stream sedimentation is seen to increase according to a second order curve with increasing angle of slope of the three experimental watershed sites (Fig. 4).

Logging-caused surface soil disturbance was undoubtedly a much smaller source of stream sedimentation than landslide erosion. The soil disturbance caused by the tree felling and log dragging (9, 11, 49) resulted in no detectable

increase in stream sedimentation at any of the three sites (4, 16). Soil erosion following slash burning was small and undetectable or masked by the greater effects of landslide erosion except at Needle Branch watershed in the Alsea study; there, surface soil erosion was thought to be the predominant source of increased stream sedimentation (4). We need to know more about surface soil structure as it may affect soil erosion after slash burning.

Increased soil erosion from timber harvest of mountainous watersheds of the Pacific Northwest was recognized more than a decade ago. Alternative yarding methods that could reach greater distances were developed to reduce road disturbance and the amount of soil reaching streams. Surface soil disturbance was also significantly reduced (11, 49) by partial or complete suspension of the logs. The watershed studies at the H. J. Andrews Experimental Forest suggest that the principal benefit from the use of alternative yarding systems such as the skyline is the elimination of roads that cross steeply inclined tributary stream channels; reduced surface soil erosion is a secondary benefit. Although we have no direct measurement from balloon- or helicopter-logged areas, observations of soil disturbance suggest that erosion and sedimentation resulting from these newer logging systems will be similar to or less than those from skyline logging.

These results from the three studies reviewed here suggest that soil erosion and stream sedimentation rates may remain elevated longest in the steepest sites where the soil is least stable. At the H. J. Andrews Experimental Forest, soil erosion and stream sedimentation are still continuing 11 years after timber harvest. At the Alsea study in the Oregon Coast Ranges where the topography is less steep, stream sedimentation returned to normal four years after clearcutting. At the Fox Creek watersheds, no increase in stream sedimentation could be detected three years after clearcutting. Results from other areas suggest that forest vegetation is a most important soil stabilizing agent on the steepest sites. In some cases, soil erosion, primarily due to mass soil movement, has increased about five years after clearcutting. This has been attributed to loss of soil strength as dead tree roots rot (37). This has also been noted on similar soil materials in Japan. There the soil erosion rate began to decline after 25 years, but was still active after 45 years (22).

The concentration of N and other nutrients in streams does increase one to two orders of magnitude following logging and fertilization. Maximum concentrations vary considerably depending upon the decomposition rate of organic matter, uptake of N by trees and subordinate vegetation, and the rate at which mineralized N is converted to NO_3. Increased concentrations from fertilization are influenced by application rate, size of area treated, density of small stream channels within the unit, and the extent to which direct application can be avoided.

The greatest effect of increased N levels would be expected if peak concentrations coincide with optimum environmental conditions for the growth of aquatic organisms. This has not happened in any of our studies. With the exception of brief peaks during summer storms, maximum concentrations and losses have been measured in the winter months when the water was cold and energy for photosynthesis minimal. Nitrogen concentrations were probably low during the summer months because precipitation was limited and any leakage from the pool of soil NO_3-N was very small.

Nitrogen entering forest streams is rapidly utilized by riparian vegetation and by organisms in the stream (23). Downstream movement will be expected to further dilute the chemical as drainage water enters from undisturbed areas. Forest streams and lakes in western Oregon and Washington characteristically contain low concentrations of N and other nutrients, and many are considered deficient in nutrients. Maximum concentration increases have not reached levels harmful to humans, and total nutrient losses are too low to affect forest production. However, it is possible that nutrient enrichment of forest streams, even though small, may gradually increase stream productivity.

The direct effect of herbicides on forest streams can be minimized simply by avoiding drift or direct application of spray materials to stream surfaces. The low concentrations which have been reported in some streams are rapidly reduced with downstream movement and do not pose a threat to aquatic life. Herbicide-induced changes in vegetation density and composition might cause some indirect effects on streams such as increased water temperature or nutrient content after the destruction of streamside vegetation, but the use of unsprayed buffer strips should minimize these effects. Herbicides are most commonly applied during establishment and early development of Douglas-fir forests. Aerial applications after full stocking and crown closure are rare; thus the potential effects on stream quality are limited to the first few years of the rotation period.

Conclusions

1. Sedimentation of forest streams after timber harvest increase exponentially with increasing angle of slope in three experimental watersheds in western Oregon. Forest roads that crossed steeply inclined stream channels caused much greater levels of sedimentation than roads on ridge tops. More time was required for soils to stabilize from clearcutting and forest roads in the steeper country. In gentle topography, increased sedimentation of streams can be prevented by well planned and administered timber harvest. Although there may be moderate increases in sedimentation on stable slopes of intermediate steepness following logging, rates may return to normal within four to five years when revegetation is rapid. In very steep

topography, where soil strength is nearly in balance with the potential for downsliding, the largest sedimentation increases are expected as a result of frequent mass erosion events. These levels persisted for more than 11 years after harvest at one site.

2. Nutrients are lost following clearcutting, but the loss decreases rapidly with revegetation. Maximum NO_3-N concentration increases in streams have remained well below toxic levels. More research is needed to relate the nutrient concentrations in streamflow to uptake by vegetation, digestion, and decomposition by soil animals and microorganisms, and logging residues. Nutrient losses by soil erosion are undoubtedly of greater importance on steeper slopes.

3. Forest fertilization-water quality studies indicate that N concentration in streams does not increase to levels exceeding published standards. Total loss of applied nutrient is small and should not have any measurable impact on eutrophication in downstream impoundments.

4. The biological effects of forest fertilization on N transformations and movement in forest soils should be investigated. Long-term consequences of repeated forest fertilization on water quality must be determined.

5. The drift or direct application of spray materials to surface waters is the principal route of herbicide entry to streams. Overland flow and leaching of herbicide are relatively unimportant factors in forest stream pollution. Carefully controlled herbicide applications are not expected to have a significant impact on forest stream quality.

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