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Impact of Forest Management on Stream Water Quality in Western Oregon

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The public has become increasingly aware of forest management and its effects on timberlands of the mountainous regions of the Pacific Northwest. Such increased interest is the direct result of growing concern for the environment and the apparent conflict of timber operations with outdoor recreation. Special attention has been directed to forest lands administered by the Forest Service and by the Bureau of Land Management because, particularly on these lands, management is also dedicated to other uses--including watershed protection for water supplies, forest recreation, and wildlife.

The need for a satisfactory environment, so pressing in the cities, is also being recognized in the forests. Standards of water quality have been set by the States of Washington and Oregon. Those who use and manage the forest are responsible for maintaining these standards. From experience, we know that water quality is directly related to the care given to the land through forest management. It is critical that persons making management decisions in the forest understand the effects of their decisions on water quality. Aspects of water quality considered here are sedimentation, forest fertilization, loss of naturally occurring nutrients, and water temperature.

SEDIMENTATION OF FOREST STREAMS

The mountainous lands of the Cascade and Coast Ranges of Washington, Oregon, and northern California contain the remaining stands of old-growth Douglas-fir forests. These forests provide raw material for the lumber, plywood, and pulp and paper industries in these states. Because these mountain ranges are barriers to precipitation from the Pacific Ocean, the river systems that originate from them carry most of the water produced in this area. These streams are sources for municipal water supplies and irrigation, habitat for anadromous fish, and prime sites for forest recreation. The increase in suspended sediment load, which frequently follows timber harvest, conflicts with other values of the forests and the streams.

In this section I will describe how erosion processes deliver soil to streams, how logging increases loss of soil, and how we can minimize erosion of the forest landscape and sedimentation of rivers.

Conflict with Other Uses

Abnormal sedimentation can be detrimental to the resident and anadromous fishery in the Pacific Northwest (14, 23). Turbid water blocks light transmission and reduces primary production of aquatic plants. Fine sediment that fills the interstices of the gravel in spawning beds reduces the circulation of water and the oxygen supply to developing fish embryos and inhibits the emergence of young salmon from the gravel.

Turbid water detracts from the recreation value of streams and lakes used for bathing, water skiing, or fishing. Increased sediment loads in streams used for municipal water supplies require additional cost for treatment to produce potable water, and dredging of sediment from rivers and harbors is a continuing expense which increases as the sediment load is increased.

Erosion Processes

Natural control of erosion on slopes.--Sedimentation results when eroded soil particles reach the stream and are carried downstream. This is a natural process that lowers mountains, provides streambeds with gravel, and is responsible for the deposition of fertile agricultural soils in the lower reaches of all major rivers.

Erosion rate is a function of several interacting factors which include vegetation, climate, topography, parent material, and soil. Vegetation is a most important factor controlling erosion (1). In humid temperate climates typical of the coastal Douglas-fir region, a nearly complete cover of vegetation dissipates the erosive force of falling raindrops. The roots of vegetation bind soil particles together and impart strength to the soil mantle.

Soil may be transported on mountain slopes either by surface soil erosion or by mass erosion of the soil mantle. Properties of soil and climate determine which erosion process is predominant. Where precipitation rate exceeds the rate that the soil can absorb water, some of the runoff will reach the stream by flowing over the soil surface. Soil is transported to the stream in this surface wash. This erosion process is of minor importance in undisturbed Douglas-fir forests. Because the soils are porous and the precipitation rate low, most of the runoff reaches the stream by flowing through the soil. Surface erosion is of minor importance compared with loss of entire segments of the soil mantle by landslide erosion. More will follow about erosion mechanisms.

Landslide erosion is the result of slope of the land, composition of soils and parent materials, and water status of the soil. In the steep mountainous land of the western Cascades in Oregon, landslide density increased exponentially with increasing angle of slope. Mountainsides that sloped at less than 40 percent were relatively more stable than slopes steeper than 50 percent (Fig. 1). This information applies to volcanic tuff and breccia parent materials which form soils that are unstable after road construction and logging. Soils from other parent materials are less erodible. Stony soils from basalt and andesite were 14 to 37 times more stable than those from tuffs and breccias (6). Volcanic parent materials, such as these, weather rapidly to silts and clays. These fine-textured soils can retain large quantities of water, but the water adds to the burden the soil must support and also reduces the strength of the soil. Landslides normally occur near peak streamflow from winter storm runoff when retention of water by the soil is at a maximum.

Landslides Related to Storm Frequency

Landslide erosion and the consequent sedimentation of streams are strongly coupled to the occurrence of widely spaced large storm runoff events. From past records we know that flooding has occurred in the Willamette Valley on the average of once every

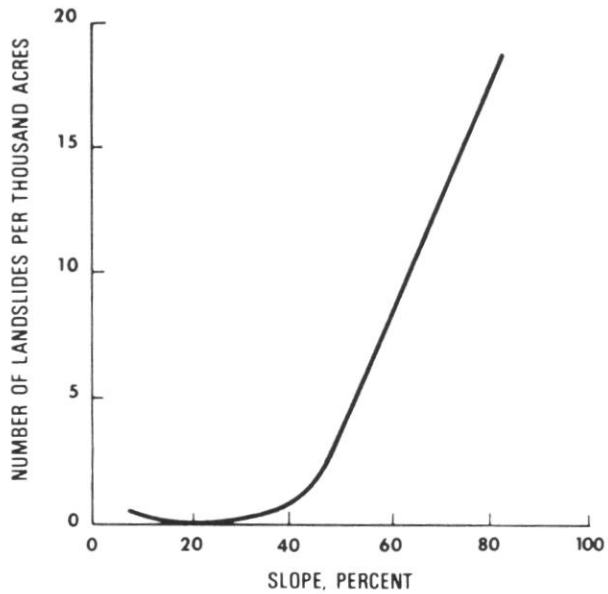

Figure 1.--Density of landslides larger than 100 cubic yards, H. J. Andrews Experimental Forest (6).

17 years (11). The storm of December 1964, which caused extensive damage to soils and property in the Pacific Northwest, was of this type. But local storms that cause soil erosion and degradation of water quality occur more frequently. An interval of 3 to 4 years for a combination of these storm types is indicated from the short period of record at the H. J. Andrews Experimental Forest (11).

Erosion and Sedimentation in Relation to Forestry Practices

Studies on experimental watersheds.--We can determine the impact of forest management practices on water quality from studies on small experimental watersheds. The relationship between the background levels of water quality (suspended sediment, water temperature, dissolved chemicals) is determined while all watersheds are undisturbed. Sampling for water quality is continued after timber is harvested. One watershed is left undisturbed to monitor the natural variation in the base level of water quality.

We have measured the water quality from combinations of clearcuts, burned slash, and forest roads on experimental watersheds in the western Cascade Range (12). In one set, a 25-percent clearcut watershed with logging roads was compared with the complete clearcut of another experimental watershed without roads. The slash was burned on both watersheds. Near the Oregon coast similar comparisons were made (3).

Effect of forest roads on erosion and sedimentation.--In steep mountainous topography, road construction causes the greatest soil disturbance of all forest management activities. Trucks, essential for transport of logs, require a network of forest roads. During construction the protective vegetation and surface soil may be removed from as much as 6 percent of the land (25). Where roads are near streams, excavated material that is cast aside on steep hillsides may reach the stream. Redistribution of drainage water and deposition of soil on steep slopes can cause soil instability and accelerated soil erosion. Of all forest roads, midslope roads--especially those which traverse steep mountain slopes and cross small tributary streams--cause the most erosion and deterioration of water quality.

Severe soil erosion and sedimentation of streams from roads can be minimized by choosing the most stable locations, using advanced engineering practices and limiting construction to dry weather. However, in steep topography and unstable soils, sedimentation can be excessive even from carefully constructed roads. In one study, during the first heavy rains following road construction, we measured a maximum of 1,780 parts per million (ppm) of suspended sediment, 250 times the load a nearby undisturbed stream. Two months later, the maximum sediment loads had subsided to 2 to 3 times the undisturbed stream and remained at this level for the following year (9). Under normal conditions of storm runoff, the technology for handling surface water from forest roads is satisfactory so long as there is no landslide erosion (12) and culverts are not plugged by debris (24).

The greatest sedimentation of streams comes from landslide erosion, common in mountainous areas with unstable soils. Landslides result from failure of the soil mantle. If the soil reaches stream channels, which is frequently the case, a torrent of stones, soil, and organic debris often scours the stream channel to bedrock. Most of these observed landslides are associated with roads (6, 24). Two such events have occurred on one of our experimental watersheds. The first, the result of a local storm, raised the maximum suspended sediment concentration to more than 6,000 ppm where, before road construction, the maximum measured concentration was 330 ppm (10). The mean winter season concentration for the year of this event was 260 ppm and 4 ppm for the roaded and undisturbed watersheds, respectively (12). The second, the result of a much larger storm that encompassed part of the area of four states, raised the mean winter concentration of one stream to nearly 2,500 ppm, while an undisturbed stream carried an average concentration of 45 ppm (12). Subsoils that were adjacent to stream channels were left bare by landslides. These areas provided a continuing source of sediment for the years that followed.

Similar results have been reported for the Oregon Coast Range (3). There, the combined effects of forest roads, clearcutting, and slash burning of an entire experimental watershed raised the mean concentration of suspended sediment to 420 ppm. On another watershed, where only 25 percent of the area was clearcut and the roads were located near the ridgetop, the mean concentration was 190 ppm. The mean concentration of the undisturbed stream was 110 ppm. These data are based on a 4-year period and only for samples taken while the streams were rising.

<u>Effect of clearcutting</u>.--Clearcutting alone has been much less damaging than clearcutting in combination with forest roads. In a watershed clearcut without roads, landslide erosion over a period of 6 years was about 2 percent of that estimated on a watershed with roads (12). There was no change in the suspended sediment concentration of the clearcut stream compared with the control stream for 2 years after clearcutting began. The increase in suspended sediment concentration that followed landslide erosion raised the mean annual concentration to only 75 ppm compared with 45 ppm in the undisturbed stream. In this case, most of the soil was trapped behind logging debris which filled the stream channel. When this soil in the stream channel was released by slash burning several years later, the mean annual concentration rose to 121 ppm (12). On the Oregon coast, clearcutting alone did not produce significant increases in suspended sediment concentration at any time (3).

<u>Effect of slash burning</u>.--Slash burning produced less sediment than either forest roads or clearcuts. No significant increase was noted in the prevailing sedimentation rate of one stream after slash burning of logged areas which covered 25 percent of

the watershed (12). The burn was of moderate intensity from these slash fires. But accelerated surface soil erosion after burning has been noted to be especially high on steep (80-percent) land surfaces bare of vegetation (19). At present, we do not know how much soil may have entered the streams because of burning, but it appears that sediment from forest roads and disturbance from clearcutting is much greater than from burning (12). There are exceptions--in the Oregon Coast Range, a large increase in sedimentation was attributed to the effects of an extremely hot slash fire (3).

Combined effects on sediment concentration.--The influence of logging and road-building on stream sedimentation is much greater during years of severe storm activity than when climatic conditions are relatively mild. The information in Table 1 compares

Table 1.--SUSPENDED SEDIMENT CONCENTRATION EQUALED OR EXCEEDED DURING YEARS OF MAXIMUM AND OF MINIMUM STORM ACTIVITY UNDER THREE TREATMENTS.[1] (IN PARTS PER MILLION).

Treatment	Mean suspended sediment for 6 years	Suspended sediment concentration exceeded during					
		Years of maximum storms			Years of minimum storms		
		No. of days per year			No. of days per year		
		1	10	100	1	10	100
Undisturbed	9	220	13	2	14	3	1[2]
100% clear-cut and slash burn	48	1,000	120	3	14	3	1
25% clearcut and slash burn with roads	430	10,000[3]	600	13	70	17	3

1/ Unpublished data from H. J. Andrews Experimental Forest, Blue River, Oregon, R. L. Fredriksen.

2/ Less than the indicated value.

3/ Greater than the indicated value.

the mean and extremes of sedimentation of streams by two types of logging and a control according to the severity of storm activity. Some variation in water quality is indicated in the stream of the undisturbed watershed. But the margin between the extremes widens in proportion to the degree of disturbance as related to the logging treatments.

The combination of forest roads and clearcutting on this steep ground is responsible for the greatest increase in stream sedimentation. Patch clearcutting with roads is commonly practiced in the Douglas-fir region of western Oregon and Washington. Even under minimum storm runoff conditions, suspended sediment loads are elevated above levels from the undisturbed watershed. Maximum values resulted from a storm that we would expect at intervals of once or twice in 100 years. This storm caused erosion at the rate of 70,000 tons per square mile (12). The mean concentration for the 6-year period was 48 times the concentration in the undisturbed watershed.

Clearcutting without forest roads caused a more restricted range of sedimentation, intermediate between clearcutting with roads and the undisturbed condition. There was no increased sedimentation early in the clearcutting period, and water quality then did not differ from the undisturbed condition as indicated by the data for minimum storm conditions (Table 1). The maximum sedimentation resulted when soil trapped behind logging debris was released by slash burning. The mean concentration for a 6-year period was about five times that in the undisturbed stream.

Oregon State water quality standards do not permit "... any measurable increase in natural stream turbidities when natural turbidities are less than 30 Jackson Turbidity Units (JTU) or more than a 10-percent cumulative increase in natural stream turbidities when the stream turbidities are more than 30 JTU ...." The sedimentation I have reported here is from steep watersheds (average slope, 60 percent) and soils that become more unstable following the construction of logging roads. Clearly, the sedimentation observed from these studies, both from clearcutting and forest roads, exceeds the limits specified by the standards (22). But there are many other areas where logging does not increase sedimentation. In two other experimental watersheds with slopes of less than 10 percent, high-lead yarding methods and forest roads have had no obvious effect upon suspended sediment concentration in the stream over a 3-year period (unpublished data).

What Can Be Done

What can be done to reduce logging-caused soil erosion and sedimentation of streams? The incompatability of logging roads and soil stability in steep topography was recognized in western Oregon more than a decade ago. At that time, development began on yarding systems that could reach farther from roads than more conventional cable logging systems and would require less road mileage. These include skyline, balloon, and helicopter. Even though the clearcut watershed used in our example was skyline logged and sedimentation exceeded present water quality standards, the maximum concentrations were less and were sustained for a shorter time compared with an undisturbed forest than were the results from high-lead yarding of the 25 percent clearcut with roads (Table 1). Although we have no direct measurements of sedimentation 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 skyline logging.

From the knowledge we have gained about soil stability, we can classify erosion potential of forest land based on type of parent material and slope of the land. Dyrness found that 94 percent of the landslides came from tuff and breccia parent materials which occurred on only 37 percent of the area; the remaining 6 percent originated from residual soils from andesite and basalt (6). There is also evidence that landslide frequency and water quality are strongly related to slope of the land. The data in Figure 1 suggest that, in the area studied, truck roads can be used where slopes are less than 40 percent. For slopes greater than 40 percent, roads should be constructed, if at all, only after examining all other possibilities for gaining access to timber. On slopes greater than 80 percent, logging may need to be severely restricted or perhaps entirely prohibited. Violations of water quality standards will frequently occur from roads on these steeper slopes.

The above study was conducted in highly unstable volcanic soils. Where parent materials are more stable, roads could be used on steeper slopes. With this information, the forest manager would know in which areas of his forest conventional logging methods would be adequate, which areas would need special methods, and which areas were too unstable for logging.

Much is being done to reduce erosion from forest roads. Prevention of erosion is less costly and less damaging to the aquatic environment than rehabilitation measures following erosion. Guidelines are established for location, design, and construction of roads to minimize soil loss (16). Reports of the effects of large storms on erosion from forest roads give feedback to those designing, constructing, and maintaining roads (24). In this way, road engineering is continually improved. Revegetation of road cut-and-fill slopes can be accomplished sooner by seeding with grass seed mixtures and by fertilizing than by natural means. The resulting vegetation considerably reduces surface erosion of these slopes (7).

NUTRIENT CHEMICALS IN FOREST STREAMS

There is much current interest in the loss of nutrient chemicals from managed forests and the effect of these chemicals on the quality of stream water. Increased nutrient levels of streams may result from the effects of logging or forest fertilization. The relevant questions about nutrient chemicals in streams are: 1) Do nutrient concentrations in forest streams increase after logging or fertilization? 2) Are the concentrations raised to levels that are toxic to living organisms? and 3) Do increased concentrations of nutrients lead to the noxious overproduction of aquatic plants?

Nutrient Concentration from Undisturbed Forests

Nutrients are retained and used very efficiently by Douglas-fir forests. These forests take up nutrients from the soil for each annual growth cycle and return them to the soil in the leaves, limbs, bark, and cones which fall to the forest floor. Nutrients released from this organic material, after decomposition by micro-organisms, are taken up again by organisms of the forest--mainly the trees. As the forest grows and increases in volume, an ever-increasing quantity of nutrients is retained in woody tissue and, therefore, is unavailable for further cycling and use. Nutrients are withdrawn from the soil nutrient pool to meet these demands. Those removed from the soil are replaced by the weathering of soil minerals, input in precipitation, and fixation from atmospheric gases.

Some nutrients are conserved very effectively by Douglas-fir forests, but others are lost in large quantities in forest streams (13). A large part of the dissolved chemical load of streams is composed of silica, sodium, calcium, and magnesium. These chemicals are released by mineral weathering in quantities far in excess of the forests' requirements for these elements, and the surplus is carried away in stream water. Nitrogen and phosphorus are found in much smaller concentrations in streams. These nutrients are seldom in soluble form in forest soils because their supply is limited. When nitrogen and phosphorus are solubilized by decompositon of organic compounds in soils, they are rapidly taken up by trees and micro-organisms.

Nutrients are also lost from the forest as soil transported to streams. These nutrients may become biologically active if they can be mineralized from suspended sediment by micro-organisms in the stream.

Nitrogen and phosphorus have particular importance in streams because of their limited supply and the potential for increased production of aquatic organisms where the concentration is increased after logging or forest fertilization. For these reasons, nitrogen and phosphorus are emphasized in the following discussion.

Nutrient Concentration after Clearcutting and Slash Burning

Clearcutting affects the conservation of nutrients in three ways: it stops the uptake of nutrients, it converts living nonmerchantable tree tissue into slash, and it often increases soil erosion. The amount of slash left on the ground will depend on the age of the pre-existing forest, its productivity, the quality of the timber, and utilization standards. A recent survey found that forest residues on clearcuts ranged from 32 to 227 tons per acre (5). The quantity of nutrients that reaches the stream from the slash may depend on whether the slash is rapidly oxidized by burning or if a slow oxidation is allowed to occur by microbial and fungal means. But in either case, nutrients are undoubtedly mineralized in quantities in excess of the requirements by vegetation and the ability of the soil to store these nutrients (13). Increased nutrient losses in streamflow can be expected until the uptake of nutrients in vegetation is again in balance with the mineralization of nutrients by decomposition and soil erosion losses subside.

Table 2.--MEAN ANNUAL CONCENTRATION OF CHEMICALS DISSOLVED IN STREAMFLOW OF CLEARCUT AND CONTROL WATERSHEDS (13). (IN PARTS PER MILLION)

Year	Nitrate - N		Ortho phosphorus - p	
	Clearcut	Control	Clearcut	Control
1966	0.020	0.010	0.024	0.026
1967[1]	0.05[2]	0.003	0.039	0.016
1968[1]	0.200	0.001	(3/)	(3/)
1971[1 4]	0.046	0.0003	0.036	0.032

1/ Following slash burning.

2/ Ammonia nitrogen concentration, 0.11 ppm.

3/ Missing data.

4/ Unpublished information.

The concentration of nutrients in forest streams has increased both from clearcutting and slash burning. But, as predicted, the concentration increase from clearcutting alone in 1966 was smaller than that from slash burning (Table 2). The mean annual nitrate nitrogen concentration in the stream in the clearcut area was double the concentration of the stream in the undisturbed watershed. The concentration rose to a maximum in 1968 and declined to about one-quarter of the maximum value 3 years later. But this level was still well above the concentration in the control stream.

The phosphorus concentration of both watershed streams was almost the same following clearcutting in 1966 (Table 2). Increased concentrations were evident the first year following slash burning--in 1967. By 1971, the difference was small and no larger than expected due to analytical error.

The maximum concentration of chemicals in the stream of the clearcut watershed closely followed the completion of slash burning. Runoff from rainfall, which extinguished the slash fire, contained maximum concentrations of 7.6 and 0.44 ppm of dissolved ammonia nitrogen and manganese (13). The 12-day average concentration of ammonia nitrogen and manganese of 1.19 and 0.11 ppm continued to exceed the permissible maximum concentration (8). Thereafter, the concentration of both chemicals declined to levels lower than the limits of detection. Nitrate nitrogen concentration rose to a maximum of 0.43 ppm in 1967--1 year after slash burning (Fig. 2). This concentration was well below the toxic limit of 10 ppm (8). By 1971, the maximum concentration had moderated to 0.065 ppm but was well above the level in the control stream (Table 2). I expect a continued subsidence of nitrate concentration in this stream as the revegetation of the watershed progresses.

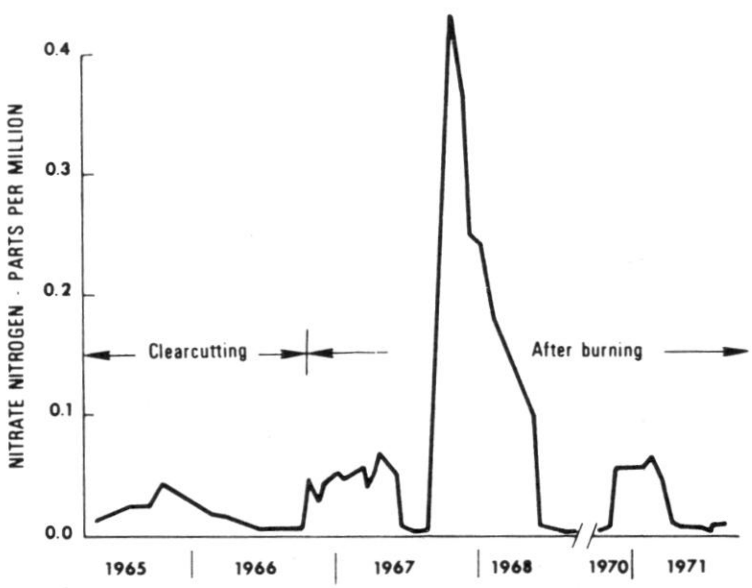

Figure 2.--Mean biweekly nitrate nitrogen concentration in streamflow following clearcutting and slash burning at the H. J. Andrews Experimental Forest, Blue River, Oregon (13), and unpublished data by R. L. Fredriksen.

The quantity of nutrients carried into the stream of the clearcut watershed by soil erosion also increased compared with the quantity in the stream of the undisturbed watershed. The average annual loss of about one-half ton per acre of soil carried about 2.6 pounds per acre of organic nitrogen into the stream compared with 0.14 pound per acre lost in the undisturbed stream (13).

Nitrogen Lost after Forest Fertilization

Urea nitrogen fertilizer has been commonly used in the Pacific Northwest for the growth enhancement of Douglas-fir forests. Urea is preferred to other fertilizer forms because of its high nitrogen content (46 percent by weight) and its pelletized form, which reduces fertilizer loss by drift. Application rates range up to 200 pounds of nitrogen per acre.

Urea pellets readily pass through the forest canopy. The principal intercepting surface is the forest floor. When the forest floor and soil are moist, ammonium ions are released after decomposition of urea. Because surface runoff seldom occurs in the conifer forests of the Pacific Northwest, rainfall carries the dissolved nitrogen into the soil. There the ammonium may be converted to nitrate by microbial means. Fertilizer nitorgen may be detected in the stream as urea, ammonia, or nitrate.

Fertilizer nitrogen may enter forest streams in several ways including direct application to streams and as a dissolved component of the soil solution. A small percentage of the total fertilizer nitrogen may enter the stream shortly after the time of application. In one of several forest fertilization monitoring projects in the Pacific Northwest, only 0.01 percent of the applied urea nitrogen was measured in the outflow of the watershed in the first 9 weeks (21). Most of this resulted from direct application of urea to the stream or by transfer to the stream in seepage flow from soil adjacent to the stream. Urea nitrogen reached a maximum concentration of 1.39 ppm; ammonium nitrogen, 0.10 ppm; and nitrate nitrogen, 0.17 ppm soon after fertilization (Fig. 3). In the summer and fall months that followed, the nitrogen concentration, essentially in the nitrate form, was small due to low streamflow (Fig. 3).

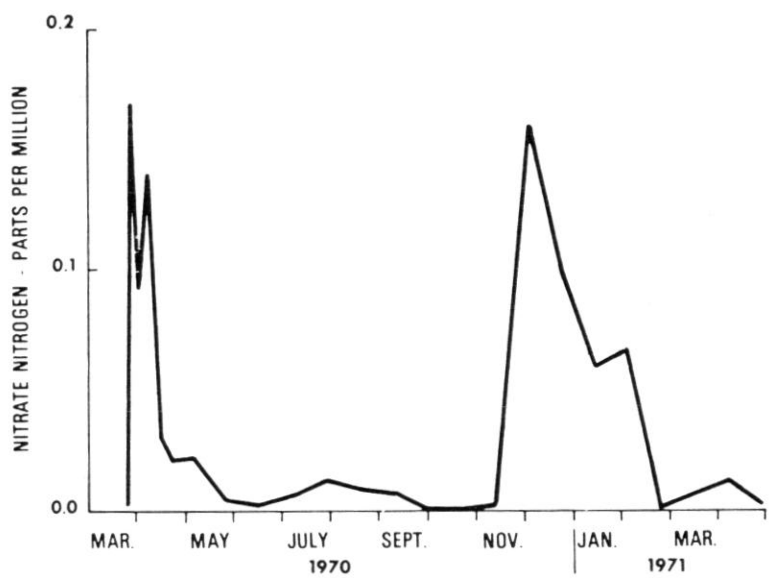

Figure 3.--Concentration of nitrate nitrogen in streamflow after fertilization with 200 pounds per acre of urea nitrogen--South Umpqua Experimental Forest, Tiller, Oregon (21), and unpublished data, D. G. Moore.

A second flush of nitrogen came in the fall and winter--7 months after application of the fertilizer (20). The nitrogen, nearly all in the nitrate form, reached a peak concentration of 0.16 ppm (Fig. 3). The nitrate concentration, which remained high through December and January, resulted in a loss of an additional 0.16 percent of the applied nitrogen. In the second winter following fertilization, there was no obvious increase in the nitrate concentration of this stream compared with the stream of the unfertilized watershed. From this, I conclude that the old-growth mixed conifer forest utilized most of the applied nitrogen within a period of 1 year.

Importance of Nutrient Enrichment of Forest Streams

The results summarized here have come from two studies on experimental watersheds in western Oregon. Although these results cannot be expected to apply directly to all logged areas and fertilization operations, we can conclude that the concentration of nitrogen and other nutrients in streams does increase from these activities in the areas studied. The maximum concentration will vary considerably depending upon the decomposition rate of organic matter, the uptake of nitrogen by trees and subordinate vegetation, and the rate at which the mineralized nitrogen can be converted to nitrate.

The greatest effect of a nitrogen concentration increase can be expected if the maximum concentration increase coincides with the optimum environmental conditions for the growth of aquatic organisms. This has not been the case in these studies (Figs. 2 and 3). The maximum concentrations and losses came in the winter season when the water was cold and the energy for photosynthesis from sunlight minimal. During the summer, the nitrogen concentration was low at a time when environmental conditions were optimum for plant production. Undoubtedly, summer nitrate nitrogen concentrations are low because precipitation is too limited to flush soluble nutrients from the soil on these clearcuts. Also, the nitrogen that enters these streams is rapidly utilized by riparian vegetation and organisms of the stream.

Increased concentration of nitrogen and other nutrients can be expected to diminish downstream from the clearcut area or the site of forest fertilization through dilution by drainage from undisturbed areas that characteristically contain smaller concentrations of nitrogen in streamflow.

What Can Be Done?

Vegetation management is undoubtedly the means whereby nutrient outflows may be regulated. Although the mechanisms of nutrient retention are not clearly understood, the loss of nitrate is prevented essentially by the presence of Douglas-fir forest vegetation.

The rapid regrowth of vegetation on clearcut and partially cut areas can be encouraged by reduction of the size of logged areas so as to create a more favorable habitat. Practices that reduce surface soil disturbance by logging or slash burning will favor vegetation regrowth.

STREAM WATER TEMPERATURE

Increased temperature of stream water frequently results from clearcutting. The source of heat is the increase in direct solar radiation reaching the stream after the removal of shade provided by the forest (2).

The principal impact of elevated stream temperatures is its effect upon the resident trout and anadromous fish. Although temperatures above 77°F may cause mortality, particularly of fish in juvenile and embryonic stages (15), reduced growth, vigor, and resistance to disease are probably the main effects of high temperature. Elevated water temperature can stress salmon and trout through the inverse relationship between dissolved oxygen content and stream temperature; at the same time, the oxygen requirement for fish respiration rises.

Maximum water-temperature increases have ranged from an instantaneous maximum of 28°F to no detectable increase. The increase of 28°F followed slash burning and stream clearance in a slow-moving portion of a coastal stream in Oregon (2). Shade from logging debris and the remaining understory vegetation can absorb and reflect much of the increased solar radiation. In one case, the shade was complete enough that no increase was noted in a watershed where 29 percent of the stream channel was in the logged area (17). Later, the water temperature of the same stream increased 12°F after the logging debris and peripheral shade were removed by channel scour resulting from a landslide. In another nearby stream flowing through an entirely clearcut drainage, residual vegetation and logging debris over the stream kept the water temperature increase to 4°F (18). The maximum water temperature increased 14°F in this same stream after logging debris was removed by slash burning and channel clearance.

The duration of increased water temperature may affect the vigor and disease resistance of highly prized game fish and commercial salmon as much as the increase in maximum temperature. In one study the water temperatures exceeded the maximum measured before clearcutting (65°F) for 30 percent of the time during the summer months (18). Though the minimum daily water temperature dipped below 65°F every night, temperature greater than 65°F persisted for 17 hours during several days in July. The maximum water temperature reached in this study was 75°F. In the Oregon Coast ranges, 85°F was the maximum temperature measured after logging and slash burning; the predicted maximum for this stream with forest cover was about 57 F°(3).

Maximum water temperatures decline as clearcut areas revegetate. Environmental conditions are conducive to rapid revegetation in the humid, temperate climate west of the Cascade Range in Washington and Oregon. Near the Oregon coast, a mean monthly maximum temperature increase of 14°F decreased to 6°F 2 years later because of the regrowth of vegetation over the stream (2).

Salmon is an important resource in the Pacific Northwest, where an acre of good stream suitable for spawning and rearing salmon has been estimated to equal or exceed the value of an acre of good timber. Unfortunately, the land base for spawning and rearing fish has shrunk due to the construction of high power dams. Water temperature can be controlled to improve the habitat for these anadromous fish by the management of shade over streams. A brush cover of vine maple, salmonberry, or elderberry may be sufficient cover on narrow streams (4). On wider streams, a buffer strip of trees is often required. Where no shade remains after clearcutting, solar heat may be reduced by planting rapidly growing vegetation such as alder, cottonwood, or various species of willow along the stream margins.

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