

COMPARATIVE CHEMICAL WATER QUALITY – NATURAL AND DISTURBED STREAMS FOLLOWING LOGGING AND SLASH BURNING

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Abstract

The loss of nutrients from an old-growth Douglas-fir forest was measured in the streams of experimental watersheds. Following timber harvest and slash burning, loss of nutrients cations increased 1.6 to 3.0 times the loss from the undisturbed watershed. A surge of nutrients that followed broadcast burning contained concentrations of ammonia and manganese that exceeded Federal water quality standards for a period of 12 days. Annual nitrogen loss following burning averaged 4.6 pounds per acre; 53 percent of this was organic nitrogen contained in sediment. Inorganic nitrogen, dissolved in the stream, made up the remaining part. Annual loss of nitrogen from the undisturbed forest was very small— .16 pound per acre.

There is much current interest in the quality of streamwater as it affects the habitat for fish and the production of organisms lower on the food chain. Streams in western Oregon and Washington, which are important rearing areas for native and anadromous fish, are supplied by water that originates largely from forested watersheds. Stream biota depend upon organic and inorganic nutrients for energy and nutrition. These nutrients originate, for the most part, from the terrestrial forest system. Inputs from atmospheric sources are small compared with sources from the terrestrial system.

Streams draining undisturbed forested watersheds often contain very low concentrations of nitrogen and phosphorus. These nutrients are of particular interest because of their short supply for organisms in the stream. Timber harvest generally accelerates the addition of these nutrients into the stream. But these increases are much smaller than additions from agricultural watersheds heavily fertilized to optimize crop production (Moe, Mannering, and Johnson 1968). The effect of increased nutrient level of streams resulting from logging and slash burning is not presently known.

Chemical nutrients in the stream are but one aspect of the interface between the forest and the stream. The utilization of chemicals by stream biota is undoubtedly also related to other changes in the stream following timber harvest. Increased solar energy absorbed by the stream, resulting from reduction of cover over the stream, increases the production of aquatic plants. Structure of the community of organisms and their metabolic rate may change due to elevated stream temperature. Sedimentation and organic materials may alter the nutrient supply of the stream. Decomposition of organic materials deposited in the stream utilizes dissolved oxygen from the streamwater—sometimes reducing the concentration to levels critical for the survival of aquatic animals.

The objective of this paper is (1) to compare the chemical nutrient quality of streams flowing from logged and burned watersheds to the stream in an undisturbed watershed and (2) to review literature pertinent to the coast Douglas-fir region.

Forest Chemical Cycles And Losses

It might be well to discuss the elements of a forest ecosystem and the principal interactions that occur between the elements. (Fig. 1). The elements of the system are:

1. The atmosphere, containing gaseous forms of carbon, oxygen, and nitrogen—chemical elements important to the existence of all life.
2. The vegetation dominated by the tree layer, responsible for carbon fixation through the mechanism of photosynthesis.
3. The dead organic remains of plants and animals, energy source for decomposer organisms.
4. The soil, which provides anchorage for plants, exchange sites for nutrients, and water for both biochemical processes and transpiration.
5. The rock mantle, which supplies most of the mineral cations to the system as a result of chemical and physical weathering.

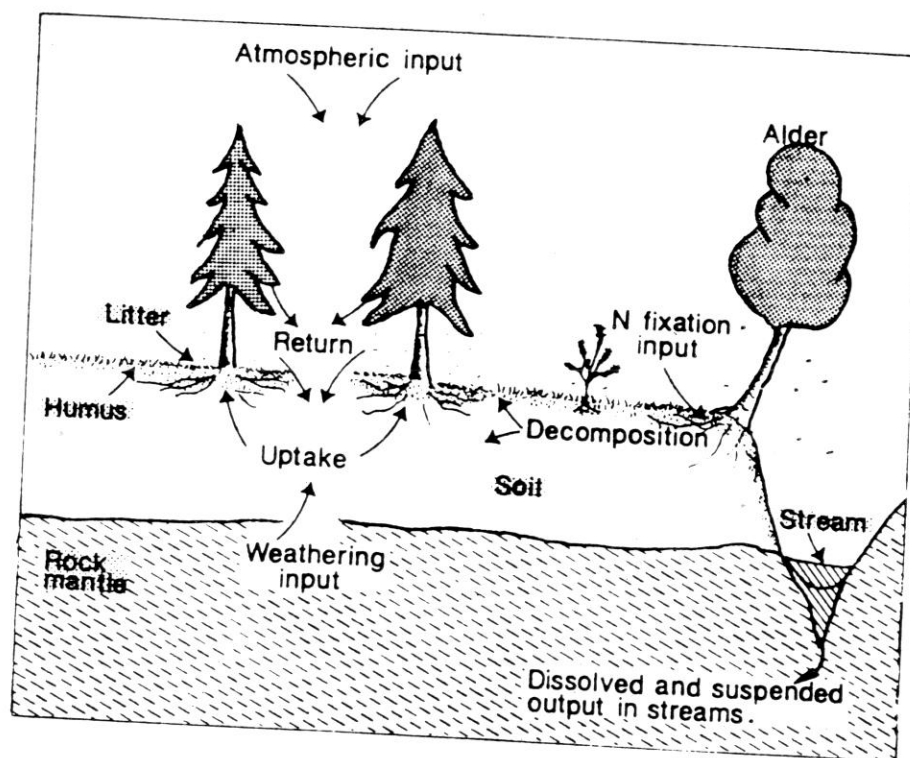


Figure 1.—Major elements and processes in a forest ecosystem.

Nutrients enter the system from:

1. The atmosphere, in precipitation, dust, or fixation by organisms (alder trees).
2. Mineral weathering (cations and phosphorus).
3. Biological inputs including those influenced by man.

Losses from the system may occur:

1. As dissolved and suspended constituents in streams.
2. By removal of materials from the land.
3. By release of N, P, and S to the atmosphere by volatilization.

The balance between inputs and losses to the forest determines the quantity of each chemical element retained. Bormann and Likens (1967) present a more complete picture of nutrient cycles in forest ecosystems.

Cycling in undisturbed forests

Cycling and reuse of chemicals is an important function in the nutrition of the forest. A certain fraction of the nutrients taken up by trees and shrubs is returned to the forest floor. Acted on by micro-organisms, the nutrients released are stored in humus or soil layers or taken up again by the vegetation. This return and reuse phenomenon is often called the inner cycle. A certain amount of the nutrient elements taken up by vegetation is retained in woody tissue. The amount retained accumulates from year to year and can become an important fraction of that contained in the forest as the stand approaches maturity (Ovington 1962). Cole, Gessel, and Dice (1967) present an analysis of a nutrient budget and flows in a young Douglas-fir stand on a nutrient-poor site.

Streams draining undisturbed forest systems contain chemical constituents not taken up by vegetation, either lost by leakage from the inner cycle or released by weathering. Nitrogen loss from undisturbed forests is very small (Cole et al. 1967). Losses of cations are also small and controlled by the quantity of mobile anions which enter the soil solution. Because there must be a balance of charge in ionic solutions, the loss of cations (K, Ca, Mg, NH_4) must be balanced by an equivalent amount of anions (McColl and Cole 1968). Bicarbonate anions formed by hydrolysis of carbon dioxide released by respiration of organisms—primarily the roots of higher plants and decomposer organisms—are the principal anion source along the Pacific Coast. Both nitrate and phosphate anions are present in small but detectable amounts.

Chemical constituents also enter the forest system in precipitation. Nitrogen, phosphorus, and potassium inputs may nearly balance losses from the system in drainage water (Cole et al. 1967). Anions in precipitation may accelerate leaching losses since anions are not readily held on exchange sites within the soil. Fortunately, concentration of anions in precipitation is generally small. However, sulfate may become an important anion near sources of industrial pollution, and chloride occurs in important amounts adjacent to the ocean (Moodie 1964).

Cycling in logged forests

Clearcutting alters the forest system by disrupting the inner cycle. Trees no longer take up nutrients, and the nonmerchantable parts of trees increase forest litter. Increased temperature and water content of the soil accelerate the activity of micro-organisms that break down forest litter. The greatly increased respiration activity of the system raises the bicarbonate anion level and leaching loss of cations from the system. Nitrogen loss as nitrate may also occur where mineral nitrogen released by decomposition of organic materials is not utilized by plants or micro-organisms. A very large nitrate loss occurred in New Hampshire following clearcutting of the forest (Likens et al. 1970). The size of this increase may have been particularly large because uptake of nitrogen was prevented by the killing of all vegetation with herbicide.

Nutrients also leave the forest system in soil and organic material eroded or deposited in the stream. Losses by this mechanism are small compared to dissolved constituent losses mainly because soil erosion from undisturbed watersheds is generally very small (Bormann, Likens, and Eaton 1969). Loss of nutrients by this mechanism may be accelerated in proportion to increased soil loss following timber harvest. This aspect of nutrient loss has received little attention.

Cooper (1969) has recently summarized information concerning nutrient output from managed forests.

Nutrient Status In Streams

Nutrient studies of streams were conducted in conjunction with hydrologic investigations of old-growth Douglas-fir forests on three small experimental watersheds. This experiment is being conducted by the Pacific Northwest Forest and Range Experiment Station on the H. J. Andrews Experimental Forest. The Experimental Forest is located 50 miles east of Eugene, Oregon, along the western slope of the Cascade Range (Rothacher, Dyrness, and Fredriksen 1967). One watershed (patch-cut) received management typical of high-lead yarding. Timber harvest removed the forest from one-quarter of the area of the watershed and the logging roads an additional 6 percent. Another watershed (clearcut) was entirely logged but contained no roads. Logging debris was broadcast burned on both watersheds following completion of yarding. A third watershed remained undisturbed throughout the experiment (control).

Nutrients in the two treated watersheds are compared to nutrients in the control watershed. Although there are no pretreatment relations for individual chemicals, data taken the fall of 1962, at the time that logging began, indicate that cation and bicarbonate concentrations were similar in all three at that time.

Water samples were collected from all three watersheds mainly during the winter season in conjunction with storm runoff. Occasional samples were taken during the relatively rain-free summer season. Sets of samples in polyethylene containers were drawn from the streams at the gaging stations within a few minutes of one another. Although sampling began in 1962, data reported here for individual nutrients are based upon 119 sample sets taken during the period from April 1965 to July 1968. Sediment samples for chemical analysis were taken in 5-gallon carboys from streams draining the clearcut and control watersheds. Twenty-one sample sets were collected from October 1966 to February 1968. Most of these samples were taken at the time of storm runoff.

Water samples taken from the streams were immediately analyzed for bicarbonate and pH. A small quantity of base and acid was added to each respective sample for nitrate and ammonia analysis. Samples were frozen until analyzed after the summer of 1966. Sample analysis was done by the Public Health Service in Portland prior to February 1967 and by the Federal Water Quality Administration in Corvallis thereafter. Sediment, separated from the bulk samples by filtration, was analyzed for chemical constituents in organic form together with the exchangeable fraction by the U. S. Forest Service in Corvallis.

Chemical Quality of Streams

Total Dissolved Solids

These streams carry small amounts of dissolved chemicals. This is characteristic of streams along the Pacific Coast from northern California to Alaska. Changes in the dissolved solids of streams following logging and slash burning can be seen in Figure 2. Total dissolved solids values on this figure are the means resulting from a linear regression of sample values from each treated watershed and the control. These annual mean values from the treated watersheds were adjusted by covariance analysis to 40 milligrams per liter—the mean concentration in the control stream for the 8-year period. Both the patch-cut and clearcut streams contained a slightly larger concentration when unlogged in 1962. These data show a large and prolonged increase in dissolved constituents following timber harvest. Dissolved content of the stream draining the clearcut watershed rose gradually during the 4 years required to complete the logging. The large rise in dissolved solids following burning in the clearcut and the lack of a rise in the patch-cut watershed may be related to the timing of precipitation following burning and also to the fact that only one-quarter of the patch-cut watershed was logged and burned. By 1968, 6 years after logging, the dissolved solids in the patch-cut stream were not statistically different from the content of the stream before logging. The clearcut stream carried a significantly larger concentration of dissolved solids in 1969.

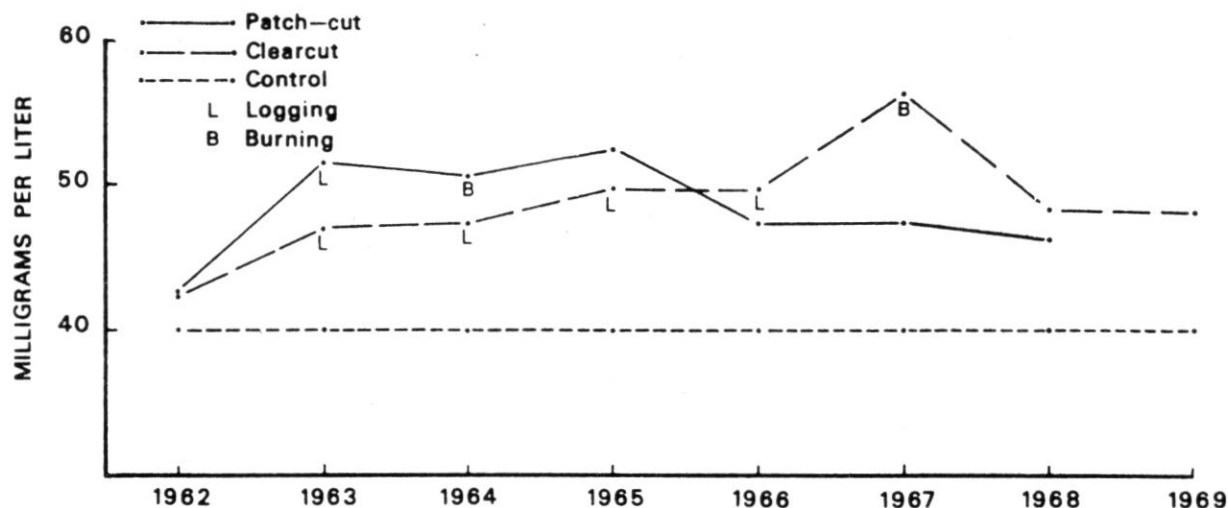


Figure 2.—Mean annual total dissolved solids concentration of streams.

Individual Dissolved Constituents

The concentration of individual dissolved chemicals in the stream of the clearcut watershed is available for the period between 1965 and 1968. The concentration pattern of the cations sodium, potassium, calcium, and magnesium followed closely the concentration of bicarbonate—the dominant anion in the stream (Fig. 3). This figure shows bicarbonate ion concentration in the clearcut and control streams near the completion of logging and following slash burning. The annual cycle of bicarbonate ion reached maximum concentrations during the warm season coincident with maximum respiratory activity and minimum during the cold season. The concentration was temperature dependent but independent of streamflow in the control watershed. The increase due to timber harvest occurred mainly during the warm season. During the coldest months, the clearcut and control stream carried nearly the same concentration. The maximum flux of cations and phosphorus followed slash burning, but the flux of nutrients subsided rapidly. The concentration of the two streams differed by less than 1 milligram per liter of bicarbonate by early January 1967.

Maximum concentrations following slash burning exceeded maximum permissible concentrations (Federal Water Pollution Control Administration 1970) in the case of ammonia and manganese (Table 1). Although concentration of all constituents in the stream of the clearcut declined during the 12 days following slash burning, the concentration was equal to or exceeded the concentration measured in the control stream. Both ammonia and manganese concentration continued to exceed permissible limits during the 12-day period. Concentration of both constituents declined to levels smaller than limits of detection after November 1, 1966, where they remained until sampling ended.

Mean annual concentrations of cations and bicarbonate in the stream of the clearcut watershed consistently exceeded the concentrations in the control stream (Table 2). Concentration of all chemicals increased markedly following slash burning. The increase was largest for the divalent cations—calcium and magnesium.

Table 1. Comparison of maximum measured concentrations of chemical nutrients in the stream of the clearcut following slash burning with those in control stream.

Nutrient	Permissible limit ¹	Maximum measured	Clearcut	Control
			12-day average	
		--mg/l--		
NH ₃ -N	0.5	7.6	1.19	.. ²
NO ₃ -N	10.0	0.60	0.43	.01
Na		6.7	4.90	3.0
K		4.4	1.89	.49
Ca		31.0	17.0	4.1
Mg		10.8	6.4	1.3
PO ₄ -P		.13	0.05	.05
HCO ₃ -C		21.6	15.8	4.11
Fe	0.3	0.04 ² ²
Mn	0.05	0.44	0.11 ²

¹Federal Water Pollution Control Administration (1970).

²Below the level of detection.

Table 2. Mean annual concentration of dissolved chemicals of streams draining clearcut and control watersheds (milligrams per liter)

Chemicals	Logging only		Following slash burning			
	Clearcut	Control	1967		1968	
			Clearcut	Control	Clearcut	Control
NH ₃ -N	-----	-----	.11	.003	.001	.000
NO ₃ -N	.020	.010	.05	.003	.200	.001
Na	2.7	2.6	2.6	2.0	-----	-----
K	.43	.42	.43	.33	.38	.22
Ca	4.8	3.3	5.8	2.8	5.0	3.0
Mg	1.2	.7	1.9	.8	1.3	.6
PO ₄ -P	.024	.026	.039	.016	-----	-----
HCO ₃ -C	4.6	3.5	5.1	3.7	3.2	2.9

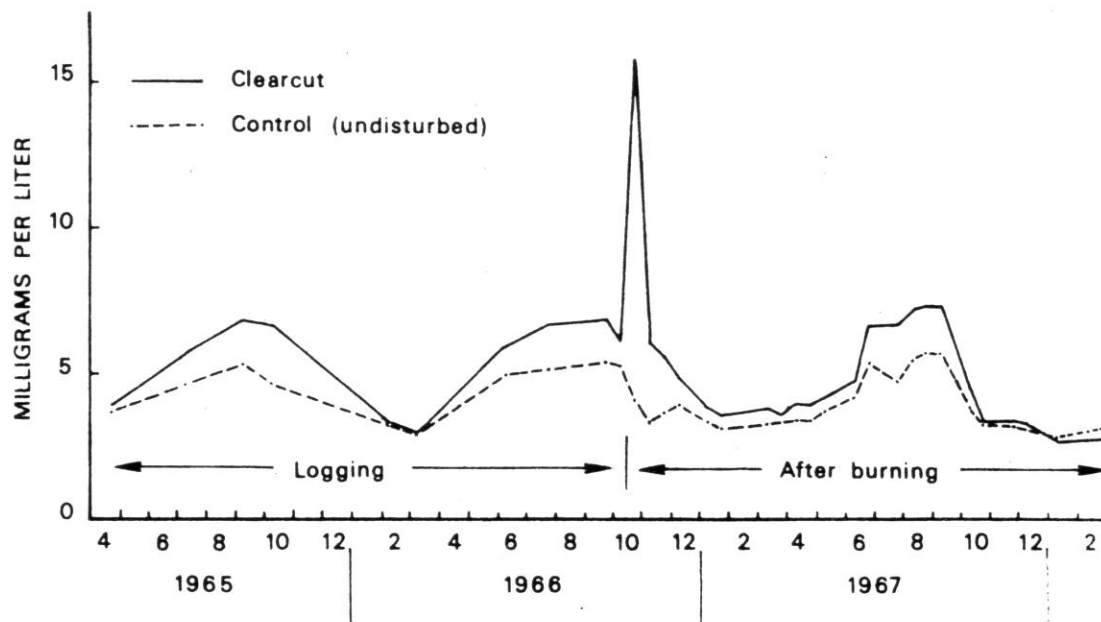


Figure 3.—Bicarbonate carbon concentration of streams after logging and after broadcast burning on the clearcut watershed.

The concentration of the two forms of nitrogen and phosphorus is about two orders of magnitude lower than the dominant cations. Nitrogen appears in the control stream as nitrate—the end product of nitrification (Fig. 4). The disappearance of nitrate from the control stream coincides with the time that analyses were

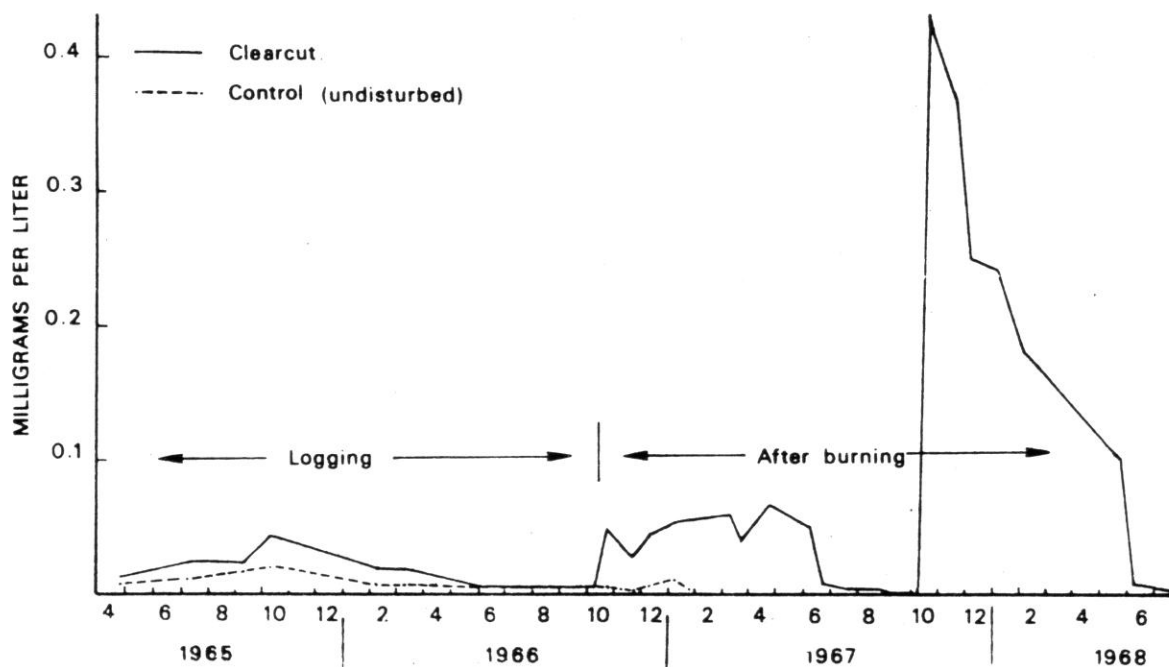


Figure 4.—Nitrate nitrogen concentration of streams.

begun in Corvallis. Concentration rise in the clearcut was small during logging but rose following burning; it increased to even greater levels the second year following burning. Minimum nitrate concentrations occur in both streams during the summer months when organisms of the forest and the streams actively use nitrogen.

Mean annual concentrations of nitrogen and phosphorus are shown in Table 2. In nitrate form, the nitrogen level was double the concentration in the undisturbed stream at the completion of logging in 1966. The concentrations involved were very small. Nitrogen concentration was greatly increased the year following slash burning in 1967. Two-thirds of this occurred in the form of ammonia while the remaining part was nitrate. Virtually the entire ammonia loss occurred within 2 weeks following the slash fire. Nearly the same nitrogen concentration, measured the second year after burning, appeared in the stream as nitrate.

Inorganic phosphorus concentration was about the same in both streams at the completion of logging, but in the clearcut the concentration was double the control stream following burning. Unfortunately, phosphorus analyses were not continued the next year.

Because both nitrogen and phosphorus are present in streams at very low concentration, the rate of photosynthesis by algae and other aquatic plants in lakes and streams may be limited by the concentration of these nutrients.

Summer levels of nitrogen and phosphorus shown (Fig. 5) are the concentrations remaining after uptake by aquatic organisms upstream of the gaging station. However, one would expect a much greater activity in the stream of the clearcut where light energy reaching the stream is much greater. Cause of the apparent nitrate

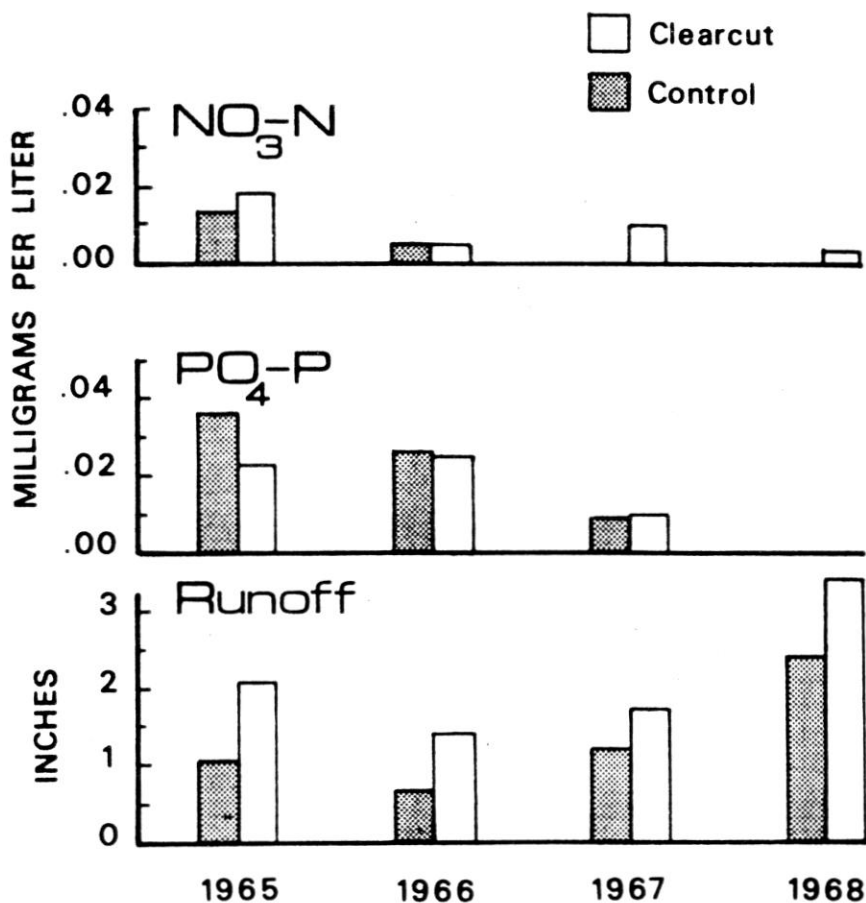


Figure 5.—Dissolved chemicals in summer runoff.

increase during logging in 1965 but not in 1966 is not known. However, the amounts involved are comparatively small. Although the concentration differed the 2 years following burning, because of differences in streamflow, the amount was nearly equal—at about .005 pound per acre. Phosphorus data indicate only small differences in concentration between watersheds regardless of treatment. However, losses are slightly greater because of increased summer flow.

The acid-base balance of the clearcut stream remained near neutral throughout the year within the range from pH 6.5 to 8.0. The mean annual pH and the pH range in the control stream were the same as the clearcut stream. The pH difference for samples taken within 2 weeks following slash burning were up to one-half pH unit higher in the clearcut. Otherwise, differences were small and compensating in the two streams.

Losses of Chemical Constituents in Streams

Loss of Dissolved Constituents

Losses of dissolved chemicals were calculated by the product of concentration and streamflow. Annual streamflow from the clearcut watershed was nearly 1.5 times the control watershed for the period from 1966-68. This increase resulted from reduced transpiration following logging (Rothacher 1970).

Annual losses of cations and bicarbonate, calculated in this manner, exceed the previous concentration data due to the increase in streamflow (Table 3). Although the amounts involved are quite large, the increases are moderate. Maximum increases occurred during the year following burning as would be expected from the previous concentration data.

Table 3. Total annual dissolved chemical loss in streams draining clearcut and control watersheds (pounds per acre)

Chemicals	Logging only		Following slash burning			
	1966		1967		1968	
	Clearcut	Control	Clearcut	Control	Clearcut	Control
NH ₃ -N	-----	-----	1.34	.025	.010	.000
NO ₃ -N	.23	.07	.62	.025	2.15	.007
Na	30.8	18.6	31.7	16.8	-----	-----
K	4.8	3.0	5.4	2.8	3.1	1.6
Ca	54.3	23.6	72.7	23.5	54.7	21.4
Mg	14.0	5.0	23.4	6.7	14.3	4.3
PO ₄ -P	.27	.19	.49	.13	-----	-----
HCO ₃ -C	51.3	25.0	64.0	31.0	35.5	20.7

Losses of nitrogen and phosphorus were expected on the basis of concentration data (Table 3). Nitrate loss from the clearcut watershed at the completion of logging was 3.3 times the loss from the control watershed. Loss of nitrogen was greatly accelerated following slash burning and was nearly equal at 2 pounds per acre for both years. The proportions of ammonia to nitrate in the clearcut stream were two to one as previously indicated. Losses from the control stream were very small and amounted to .05 pound per acre in 1968. The increases ranged from 80 to 300 times because of the difference in background concentration. Loss of inorganic phosphorus from the clearcut was much smaller than nitrogen loss and proportional to the streamflow increase in 1966. The loss after slash burning was larger (3.8 times). Though the increases are small, the potential for impact is large in streams because of the low phosphorus content.

Losses on Sediment

Nutrient chemicals also enter the stream attached to sediment or contained in organic sediment materials. Amounts of chemicals added are the result of the concentration carried on the sediment and the amount of sediment entering the stream. Large increases in the loss of all chemicals are evident for both years (Table 4). A reduced loss in 1968 was largely the result of lower sedimentation. Suspended sediment loss was 14 times the control in 1967 but dropped to half that amount in 1968 (Fredriksen 1970). It is noteworthy that loss of manganese on sediment was the principal mechanism for loss of this element which was essentially absent from these streams in dissolved form. Although increases were large, the amounts lost were small compared with

Table 4. Annual loss of chemical constituents adsorbed on mineral sediment plus that contained in suspended organic material (pounds per acre)

Chemicals	Following slash burning			
	1967		1968	
	Clearcut	Control	Clearcut	Control
Organic N	3.4	.14	1.7	.14
K	1.1	.023	.7	.022
Ca	2.8	.2	1.4	.4
Mg	1.7	.027	1.0	.027
Mn	1.4	.02	.7	.02

dissolved chemical losses except for nitrogen and potassium (Fig. 6). As can be seen from this figure, loss of organic nitrogen on sediment averaged 54 percent of the total loss for the 2 years combined. Potassium was only 17 percent of the 2-year loss.

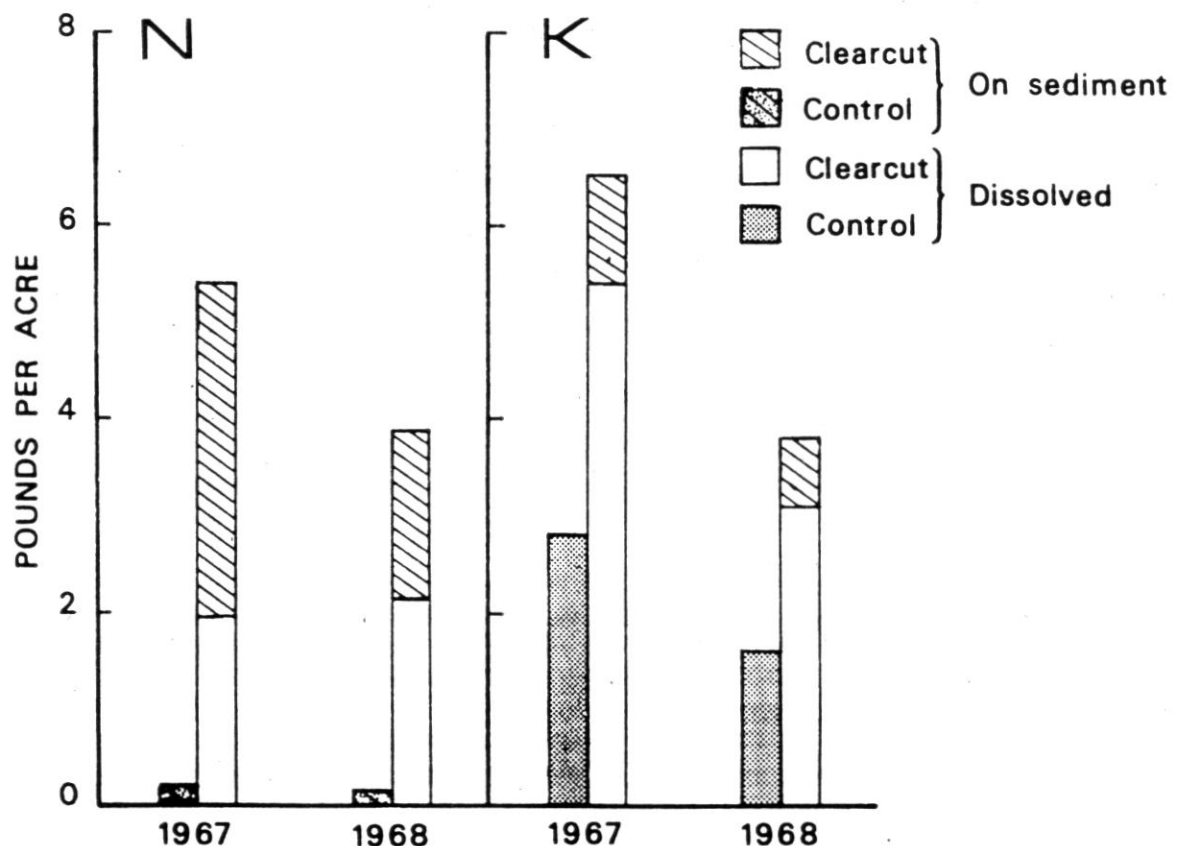


Figure 6.—Total annual loss—dissolved and on sediment in streams following slash burning.

Discussion

Results of this study indicate that the loss of chemical nutrients from the terrestrial system of the forest into the aquatic system of the stream increased following logging and slash burning. Concentrations of ammonia and manganese following slash burning initially exceeded Federal Water Pollution Control Administration standards. Such levels did not persist in the stream for more than 12 days. Gessel and Cole (1965) reported increases in loss of dissolved nitrogen, phosphorus, potassium, and calcium from clearcutting that are in the same order of magnitude as the results of this study. The only other results from the Pacific Coast of North America reported no increase in cation concentration following wild fire in the Sierra Nevada of California (Johnson and Needham 1966). The small increases in concentration of cations from the H. J. Andrews Experimental Forest that resulted from slash burning may have occurred in the study of Johnson and Needham but were too small to be detected by their experimental design. They did not examine water samples for dissolved nitrogen.

Results reported in this study suggest that management can minimize the flux of chemical constituents into the stream in at least two ways. First, more than half of the nitrogen entered the stream combined with or adsorbed to sediment. Measures taken in the planning and administration of timber sales that minimize soil loss into the stream can reduce the amount of this valuable plant nutrient that enters the stream. Perhaps particular management emphasis should be given to steep mountainous land where high productivity is maintained by the presence of comparatively deep soils. Sedimentation can be particularly heavy from logging operations in this terrain (Fredriksen 1970). Secondly, loss of nitrate in dissolved form in streams may be retarded where slash burning can be avoided. The nitrate loss may be reduced by the amount of nitrogen that is utilized by vegetation left after clearcutting. Slash burning destroys much of this vegetation. Neal, Wright,

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and Bollen (1965) reported increased ammonium and nitrate ion concentration in the soil following slash burning. These same ions were found in runoff following burning in this study.

The importance of certain aspects of the losses from the terrestrial system resulting from timber harvest can be appreciated on the basis of data presented here. First, loss of the principal cations may not be important where elements are supplied in large quantities by chemical weathering of soil parent materials. Large annual losses in the control stream are surplus to the annual uptake of these cations by the old-growth Douglas-fir forest on this watershed. Secondly, annual loss of dissolved nitrogen following slash burning (2 pounds per acre) is nearly equivalent to the total nitrogen input that we are presently measuring in rainfall. Thus, nitrogen should begin to accumulate in the system as solution losses decline to levels measured in the control stream. Additional nitrogen inputs to the system from symbiotic fixation by *Ceanothus velutinus* Dougl., present in early successional stages of revegetation on the clearcut watershed, may be a more important nitrogen input to the system. Estimated annual fixation rates of 50 to 60 pounds per acre measured in greenhouse studies (Delwiche, Zinke, and Johnson 1965, Wollum and Youngberg 1964) are open to question when applied to field conditions (Zavitkovski and Newton 1968).

Research currently in the planning stages will indicate the additional possible fixation by mosses and lichens. The importance of phosphorus and sulphur losses as dissolved nutrients and in connection with sediment needs further investigation.

Even less is known concerning the importance of the addition of nutrients to the aquatic stream system. The importance of changes in nutrient level in the stream may be reflected as ecological changes to stream fauna and flora. Timber harvest causes changes to the stream which, coupled with increased nutrition, could lead to increased growth of algae. Increased sunlight to the stream that results from removal of shade by timber warms the stream and increases the potential for primary production of aquatic vegetation. Productivity of the stream may also be raised depending on the amount of the essential nutrients in organic form that can be utilized by stream organisms. This idea can be illustrated from data reported in this study. Assuming a carbon to nitrogen ratio of ten to one in aquatic plants and that all of the dissolved nitrogen is utilized, the .005 pound per acre lost during the summer in the clearcut stream would result in a fixation of .05 pound of carbon. However, if the organisms could recover half of the nitrogen contained in the sediment lost from the watershed the first year following burning, an additional 17 pounds of carbon could be fixed in the stream. This amounts to about 5.5 tons of carbon per square mile of forest logged and burned based on the assumptions made. These results are hypothetical at this point, but they suggest possible changes in the streams of watersheds currently being managed for timber production.

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