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Clearcutting Affects Stream Chemistry in the White Mountains of New Hampshire

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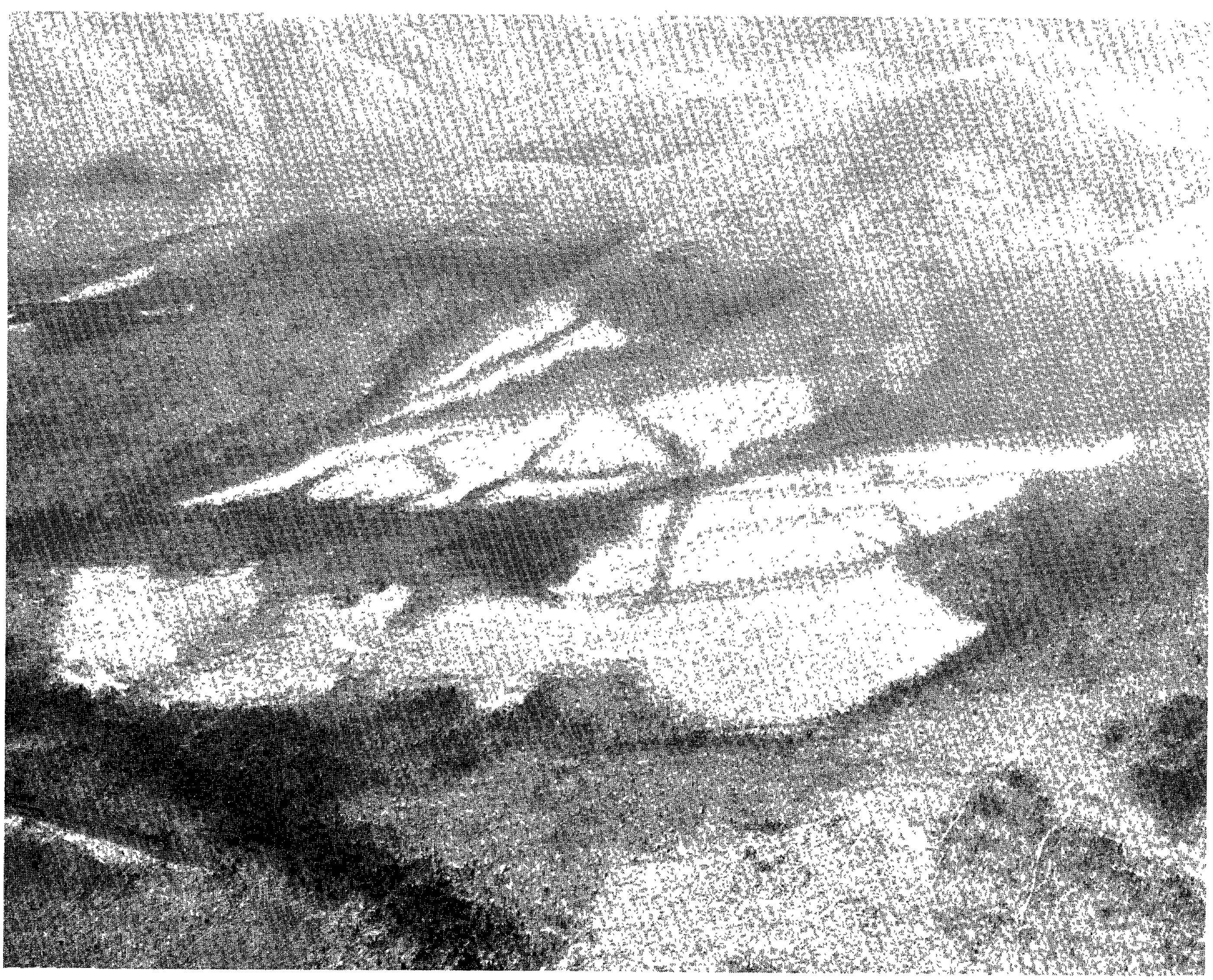

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Abstract

Clearcutting of northern hardwood forests in New Hampshire resulted in accelerated loss of dissolved nutrients to streams similar to that shown in experimental studies at Hubbard Brook. Stream water samples were collected during 4 years from nine watersheds that had been completely clearcut and from five nearby reference watersheds that were uncut. Differences in stream chemistry between clearcut and reference watersheds were greatest during the second year after cutting. During the 4 years of the study, specific conductance of the reference streams ranged from 20 to 30 μS/cm; average pH ranged from 5.0 to 5.7; nitrate ranged from less than 0.1 to about 4.0 mg/l; calcium from 1.0 to 3.0 mg/l; ammonium from less than 0.01 to 0.05 mg/l; magnesium from 0.2 to 0.8 mg/l; sodium from 0.6 to 1.6 mg/l; potassium from 0.1 to 0.7 mg/l; sulfate from 3.0 to 8.0 mg/l; and chloride from 0.3 to 0.6 mg/l. During the second year after clearcutting, specific conductance of streams draining the cuts ranged from 22 to 68 uS/cm; average pH ranged from 5.1 to 6.0; nitrate ranged from 1.4 to 27.3 mg/l; calcium from 1.4 to 6.7 mg/l; ammonium from less than 0.01 to 0.05 mg/l; magnesium from 0.3 to 1.4 mg/l; sodium from 0.8 to 3.0 mg/l; potassium from 0.1 to 1.5 mg/l; sulfate from 2.1 to 6.3 mg/l; and chloride from 0.4 to 0.9 mg/l. During the first year after cutting, streams from the cuts were more acidic than those from the reference streams; however, they were less acidic by the end of the second year. Concentrations of most ions in streams from clearcuts approached reference levels by the end of the fourth year after clearcutting, though streams from clearcuts remained less acidic by nearly a whole pH unit, sulfate remained depressed, and potassium remained elevated. During the 4 years following cutting, stream exports from cut sites exceeded those from reference sites by 57 kg/ha for inorganic nitrogen, 61 kg/ha for calcium, and 15 kg/ha for potassium.

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Introduction

Even-age forest management is practiced widely with many forest types in the Northeastern United States (USDA 1973). However, site changes created by clearcutting at the end of the management cycle may cause major changes in soil fertility and in water quality of streams flowing through the cut areas. Our paper examines these changes as they occur in northern hardwood forests on glaciated soils of the White Mountains of New Hampshire.

Soils underlying these forests are spodosols formed on glacial till and outwash. Under forest cover, these soils are characterized by organic horizons over mineral soil. Most of the available nutrients and, in turn, the majority of plant roots are found in the surface organic horizons (Hoyle 1973; Wood 1980). Because of low clay content, low basic minerals, and high acidity, the mineral horizons tend to be relatively infertile. Removal of the forest canopy during harvesting increases temperature and moisture in the forest floor, increases nitrification, and decreases uptake of water and nutrients by plants (Bormann and Likens 1979). The warmer, wetter microclimate leads to an increased rate of organic matter decomposition, nitrification, and mineralization, with a net reduction in the amount of humus (Hart 1961; Dominski 1971; Covington 1981). These processes rapidly convert unavailable nutrients in organic matter into available plant nutrients.

Abundant available nutrients, water, and light usually lead to rapid revegetation of the site by flora adapted to these disturbed conditions (Bormann and Likens 1979). However, because of the accelerated mineralization coincident with reduced net uptake and storage of nutrients by forest vegetation for the first few years after cutting, some of these available nutrients are leached to groundwater or streams (Bormann and Likens 1979). Different soils and vegetation types vary in their ability to retain these mineralized nutrients on the sites (Corbett et al, 1978; Vitousek and Melillo 1979).

In this paper, we present 4 years of postcutting data on stream water chemistry from nine clearcut watersheds dispersed throughout the White Mountains of New Hamphire. We compare stream water ion concentrations and nutrient removal between clearcut areas and adjacent uncut reference watersheds. Preliminary data from this study were published by Pierce et al. (1972), and nitrate and calcium data from these watersheds were published by Martin and Pierce (1980).

The objective of this study was to test the applicability of the findings of experimental clearcutting studies at the Hubbard Brook Experimental Forest in central New Hampshire (Pierce et al. 1970; Hornbeck et al. 1975; Likens et al. 1977) to a broader geographic area, and to document nutrient-cycling parameters that should be considered in evaluating the impact of clearcutting on site productivity.

The Study

Beginning in 1970, we examined numerous commercial clearcutting operations in the White Mountain National Forest to locate potential study sites. We located five areas with similar topography, vegetation, soils, and geology. Each area included at least one clearcut watershed and in two cases several clearcuts (Table 1). These sites had well-defined watersheds with perennial headwater streams, and all stems more than 5 cm in diameter at breast height (d.b.h.) had been cut. Each area had an adjacent or nearby uncut watershed that served as a reference (Reinhart 1967). Descriptions of the sites, volumes of trees before cutting, time of cutting, volume and species of wood removed, and maps were provided by the staff of the White Mountain National Forest.

Before cutting, all of the watersheds had been covered by second-growth forests, 50 to 100 years old. They contained the following ranges of species by volume: 1 to 40 percent sugar maple (*Acer saccharum* Marsh.); 8 to 17 percent yellow birch (*Betula alleghaniensis* Britton); 15 to 77 percent beech (*Fagus grandifolia* Ehrh.) and other northern hardwoods; and 3 to 30 percent spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* (L.) Mill.).

Methods

Stream water samples were collected twice each month from April through November—and monthly during the winter—except at Hubbard Brook and East Branch, where samples were collected weekly. Specific conductance was measured in the field. Laboratory measurements included pH, concentrations of nitrate, calcium, magnesium, sodium, and potassium. Concentrations of ammonium, sulfate, and chloride were measured but not in all streams. The methods used for collecting samples, intensity of sampling, and procedures for chemical analyses were reported by Likens et al. (1977). Mean pH was calculated by converting pH to hydrogen ion concentrations, averaging, and reconverting to pH.

Watersheds were clearcut between 1968 and 1972 (Table 1), whereas stream water sampling began in the autumn of 1970 and continued through 1974. All of the clearcut watersheds were harvested between August and December before what we term the "first year after cut" (Figs. 1-6). Since the principal objective was to estimate stream water chemistry at different times after clearcutting, it was necessary to average stream water chemistry as follows: stream water concentrations in samples taken in 1971 for all stands cut in 1970 were averaged to represent the first year after cutting; stream water concentrations taken in 1971 for stands cut in 1969 were averaged to represent 2-year-old cuts along with concentrations collected in 1972 for stands cut in 1970, and so forth. Concentrations for the reference watersheds for 1971-74 also were averaged by years.

Table 1.—Site characteristics of the watersheds

Watershed	Total area	Aspect	Slope	Soil texture[a]	Northern Hardwoods	Bedrock Geology[b]	Year of Cut[c]
	ha		*Percent*		*Percent*		
				REFERENCE			
1. Gale River	49	NW	10	sl	90	kqm	—
2. Beaver Brook	50	W	15	sl	90	kqm	—
3. Conner Brook	45	NE	32	ls	80	lfg	—
4. East Branch	8	S	15	sl	70	bg	—
5. Hubbard Brook	13	S	20	sl	95	lfg	—
				COMPLETELY CLEARCUT			
6. Hubbard Brook	10	S	35	sl	95	lfg	1970A
7. East Branch	4	S	10	sl	70	bg	1970G
8. Gale River	2	NW	10	sl	95	kqm	1970G
9. Gale River	4	NW	10	sl	95	kqm	1969A
10. Gale River	24	N	10	sl	95	kqm	1971G
11. Gale River	14	N	10	sl	95	kqm	1972G
12. Beaver Brook	20	W	15	sl	90	kqm	1971A
13. Beaver Brook	14	W	15	sl	90	kqm	1971A
14. Conner Brook	8	NE	32	sl	80	lfg	1968A

[a] sl = sandy loam, ls = loamy sand. Conner Brook soils are in the Berkshire-Lyman-Marlow association; all other sites are in the Becket-Lyman-Hermon association.
[b] kqm = Kinsman quartz monzonite, bg = Bethlehem gneiss, lfg = Littleton formation sillimanite-zone gneiss with mica shist intrusions.
[c] A = autumn, October through mid-December; G = growing season, August and September.

Construction of the nutrient budgets required some assumptions. Previous work (Martin 1979) indicated that although the quantity of precipitation is quite variable throughout the White Mountains, precipitation chemistry is not. Consequently, precipitation chemistry was measured only at the Hubbard Brook Experimental Forest. Precipitation quantity was drawn from the National Weather Service volunteer network (NOAA 1971, 1972, 1973) and from Hubbard Brook. Volume-weighted ionic concentrations in precipitation from Hubbard Brook were summed by month. Monthly concentrations (mg/l) were multiplied by the estimated monthly precipitation quantity (l/ha) for each site. Then the total estimated monthly quantity for each ion from each site was summed for the year to give the input data as kg/ha/yr for each watershed. Streamflow estimates were derived for each area from a hydrologic model developed at the Hubbard Brook Experimental Forest (Federer and Lash 1978). This model estimates streamflow increases due to cutting and decreases due to revegetation. Output budgets were calculated by averaging monthly ionic concentrations in stream water and multiplying by the estimated monthly streamflow for each site and summed for the year.

Results

Although the results presented here are averages, the highest concentrations (as represented by the range bars in Figures 1–5) generally are from one particular watershed and the lowest are consistently from another. The differences in the results between cut watersheds probably reflect local differences in climate, weather, topography, soils, and glacial till. We have attempted to minimize these differences by averaging the data. In so doing we can discuss the general effects of harvesting on water chemistry in the region. But it must be realized that at any one site, the effects may be larger or smaller.

Specific Conductance

Specific conductance of the streams that drained the reference watersheds ranged between 20 to 30 μS/cm with few exceptions throughout the 4 years of the study (Fig. 1). No single stream was consistently higher or lower than the rest. A seasonal pattern was evident with the lowest values occurring in the summer and the highest values in the winter.

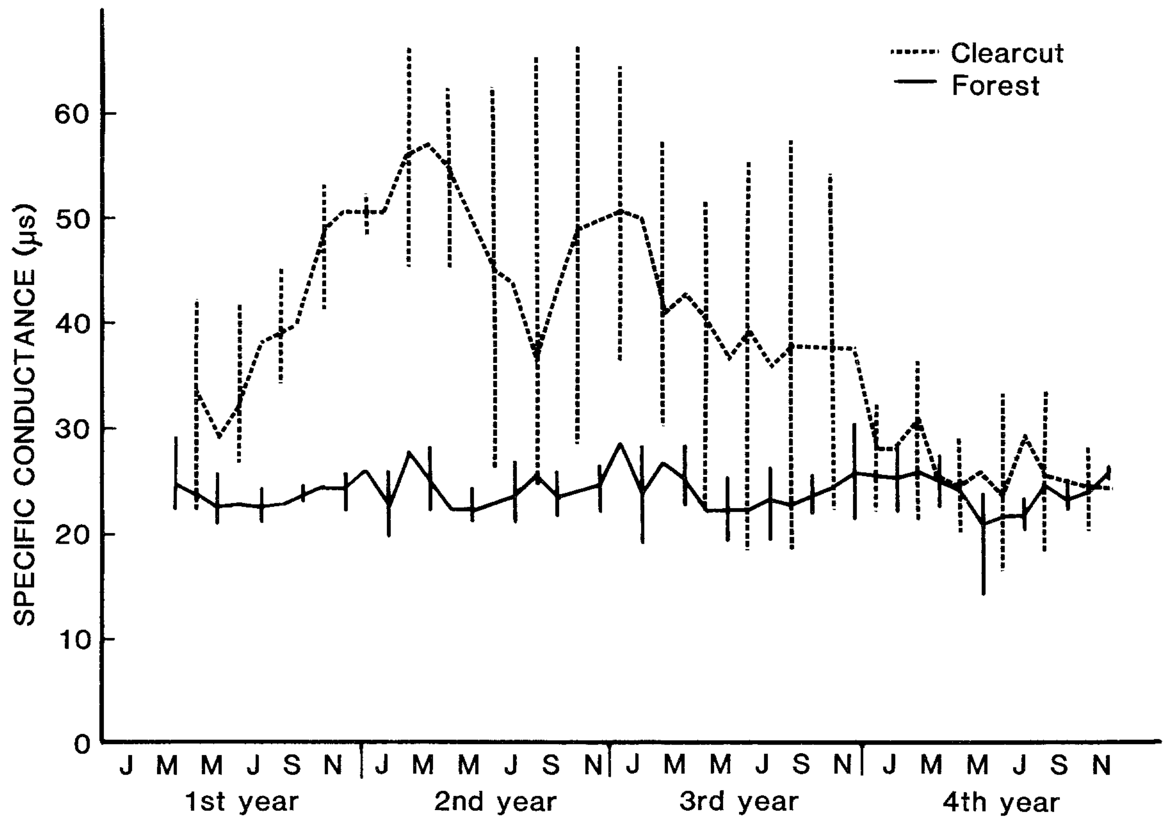

Figure 1.—Mean monthly specific conductance of streams from both forested and clearcut watersheds for 4 years after cutting (vertical bars represent the range of mean monthly data among the individual streams studied).

The first winter after cutting, specific conductance of the streams that drained clearcut watersheds was similar to that of the reference streams. But early in the first spring after cutting, the conductance began to rise. It increased steadily through the summer, autumn, and winter to peak during the spring of the second year after cutting (about 18 months after cutting). Although there was variation among watersheds, specific conductance of all streams rose steadily during this period. The maximum values for each stream during the first 18 months after cutting ranged from 48 to 66 μS/cm.

In most cases, conductance declined the second summer after cutting, only to increase again the next autumn (about 26 months after cutting). Specific conductance of the stream draining the clearcut at Hubbard Brook dropped to 24 μS/cm in September (21 months after cutting) and rose to only 35 μS/cm by December. At the other extreme, two streams at Gale River dropped only to about 59 μS/cm during the second summer after cutting, and rose to nearly 69 μS/cm during the autumn (25 months after cutting).

During the third year after cutting, specific conductance declined in all streams draining cut areas but the differences among these streams remained large, as indicated by the relative size of the range bars (Fig. 1). The streams at Hubbard Brook dropped below reference values while the two streams at Gale River remained above 47 μS/cm.

During the fourth year after cutting, the specific conductance of all of the streams draining clearcut watersheds returned nearly to reference levels. The variation among streams also was greatly reduced during the fourth year.

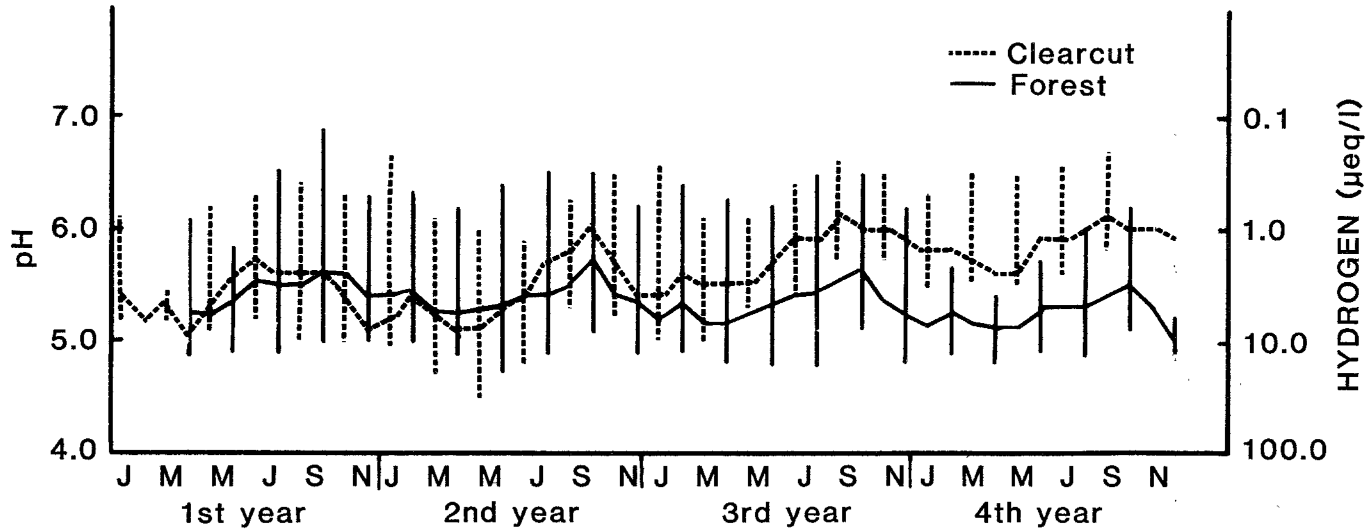

Figure 2.—Mean monthly pH of streams from both forested and clearcut watersheds for 4 years after cutting (vertical bars represent the range of mean monthly data among the individual streams studied).

pH

The range of pH was considerable both within and among the reference streams (Fig. 2). The average pH of all five reference streams ranged from 5.0 to 5.7. But the most acidic reference stream ranged from pH 4.7 to 5.1, while the least acidic dropped below pH 6.0 only six times in 30 months. Generally, conditions in the streams were most acidic during the snowmelt period in the spring, and least acidic during leaf fall in autumn.

During the first and second years after cutting, the mean and range of means of pH for all streams draining the clearcut watersheds were similar to those of the reference steams (Fig. 2). Although the average acidity for streams in reference and clearcut watersheds was similar, individual paired watersheds exhibited marked differences. For example, two streams from clearcut watersheds remained more acidic than their reference counterparts—with an average pH of about 5.5 versus 6.4 throughout the second year after cutting. But one stream from another clearcut remained less acidic than its reference, with an average pH of about 6.3 versus 5.5, throughout nearly all of the second year after cutting except in late summer and early autumn when their pH levels were similar.

In the third and fourth years after cutting, all streams draining clearcuts were less acidic than their paired reference watersheds; the average pH was about 6.0 versus 5.4 (Fig. 2).

Nitrate

Nitrate concentrations (Fig. 3) in the streams that drained the reference watersheds ranged from less than 0.1 mg/l to about 4.0 mg/l. A seasonal trend was apparent; concentrations were higher through the winter and spring than during the summer, a pattern similar to that reported in long-term studies of forested watersheds at Hubbard Brook (Likens et al. 1977). During the summer, nitrate concentrations dropped to less than 0.5 mg/l in some streams but remained higher than 2.0 mg/l in others.

All of the clearcut watersheds were harvested between August and December. The first year after cutting, nitrate concentrations in most of the streams draining these watersheds were higher than in the reference streams by February (2 to 6 months after cutting). Although there was wide variation among streams, nitrate concentrations in all cases continued to increase throughout the first year after cutting. Nitrate concentrations in all streams were highest between January and April of the second year (16 to 20 months) after cutting. This maximum value ranged between 23 to 28 mg/l among streams. Following the peak, nitrate in most of the streams began a steady decline that approached reference levels by the middle of the fourth year (48 to 54 months) after cutting. This decline was much more rapid in some cases than in others, as the range lines in Figure 3 indicate.

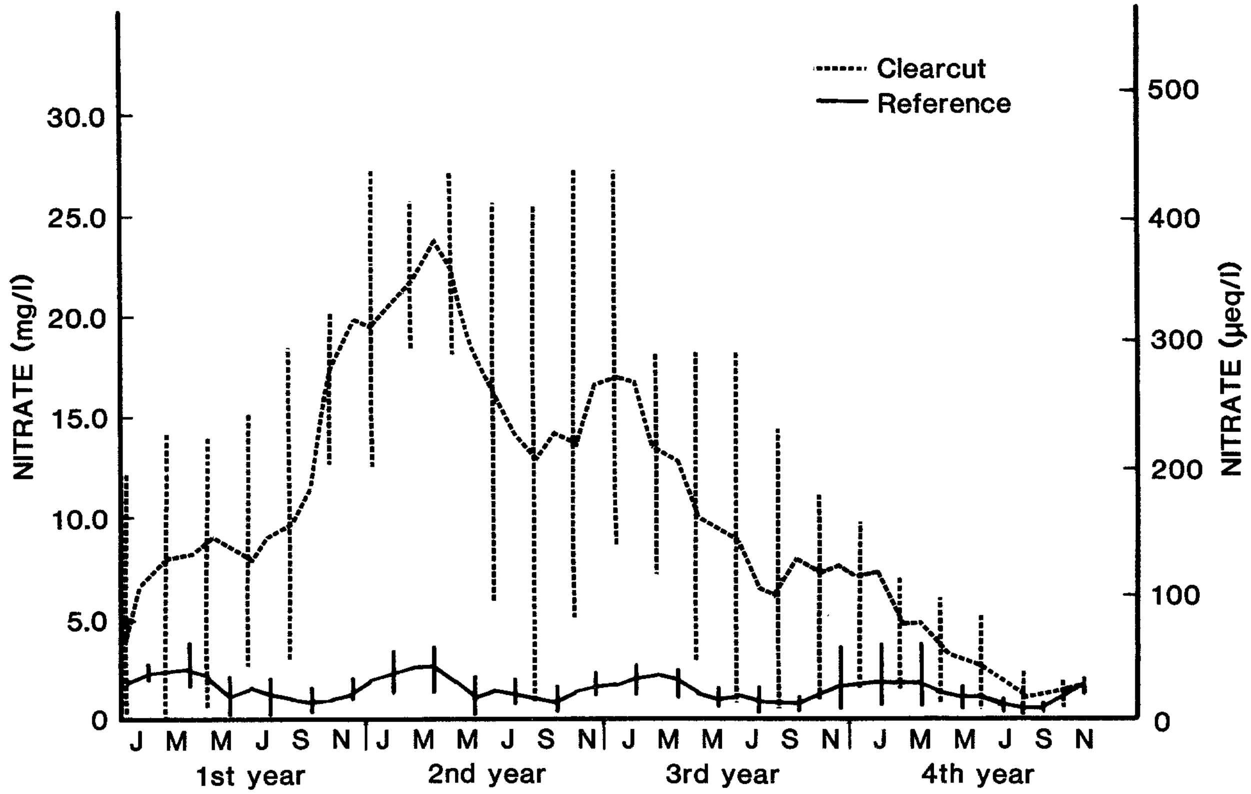

Figure 3.—Mean monthly nitrate concentrations in streams from both forested and clearcut watersheds for 4 years after cutting (vertical bars represent the range of mean monthly data among the individual streams studied).

Ammonium

Ammonium concentrations were measured in stream water from three pairs of reference and clearcut watersheds. Ammonium ranged from less than 0.01 to 0.05 mg/l, inclusive. No seasonal trends, treatment effects, or differences between watersheds were apparent.

Calcium

Calcium concentrations in the reference streams ranged from 1.0 to 3.0 mg/l (Fig. 4). Variation among streams or over time within individual streams was slight.

Calcium concentrations in the streams draining harvested watersheds began to rise immediately after clearcutting. Values generally were highest (6.5 to 8.1 mg/l) during the winter of the second year (12 to 16 months) after cutting. Calcium in the stream at Hubbard Brook (lower limit of range lines in Figure 4) had returned to reference levels 28 months after cutting; but in two streams at Gale River (upper limits of the range bars in Figure 4), calcium concentrations were twice those of reference levels 50 months after cutting.

Magnesium

Magnesium concentrations in the reference streams were stable, varying by no more than 0.1 mg/l over the 4 years of the study. There was some variation between watersheds: one averaged 0.2 mg/l; another averaged 0.8 mg/l.

Following clearcutting, magnesium concentrations generally rose slowly throughout the first year (Fig. 5) and peaked in the second year after cutting. In some streams, this peak occurred early in the spring of the second year, in some in midsummer, and in others not until late autumn (2 full years after cutting). Generally, this second-year peak, as high as 1.4 mg/l, was 3 to 5 times as large as the concentrations in the paired reference streams.

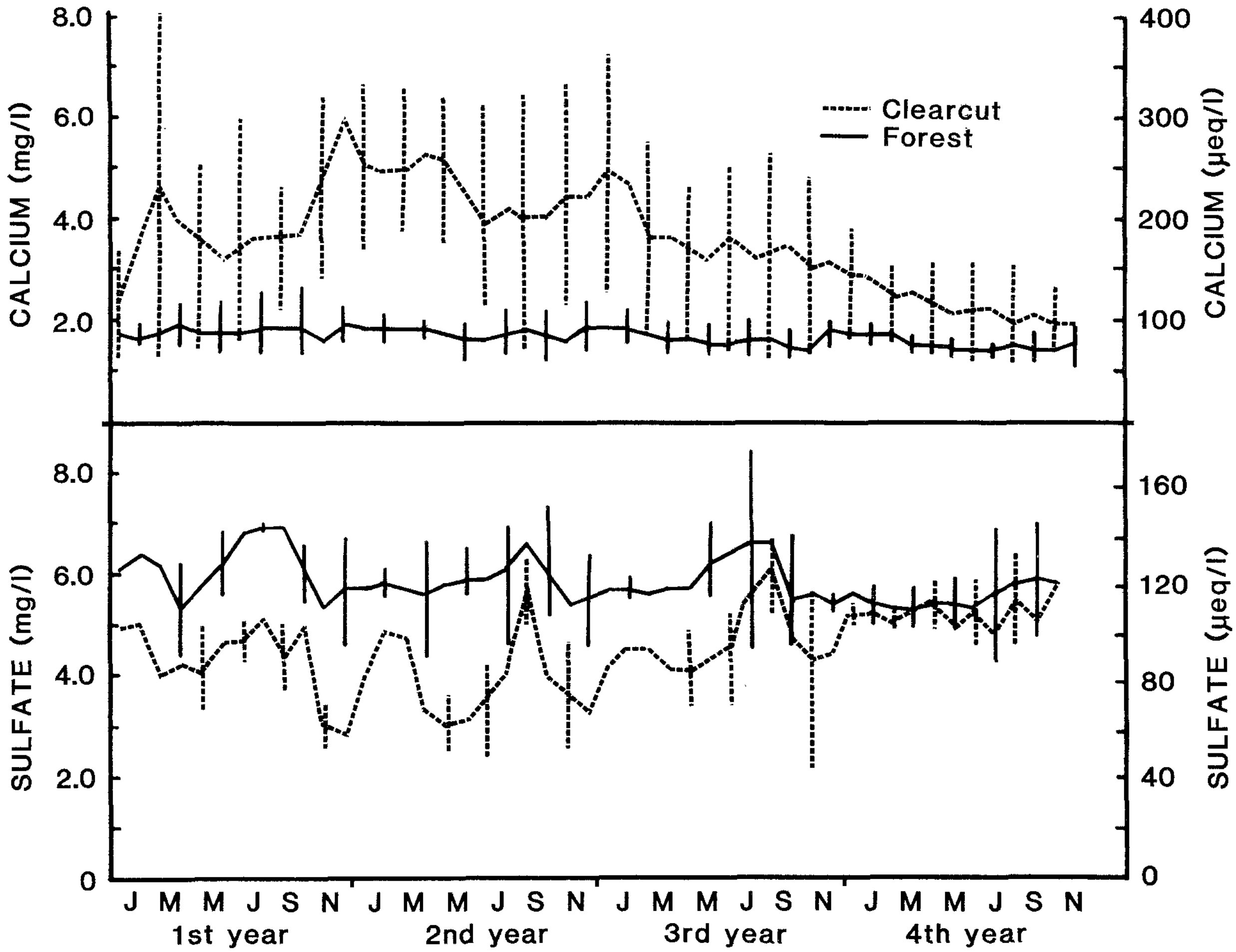

Figure 4.—Mean monthly calcium and sulfate concentrations in streams from both forested and clearcut watersheds for 4 years after cutting (vertical bars represent the range of mean monthly data among the individual streams studied).

Magnesium concentrations declined slowly throughout the third and fourth years after cutting. Examination of individual grouped watersheds revealed that magnesium concentrations in about half of the streams returned to reference levels by the summer of the fourth year, while the remainder at 0.6 mg/l were at least double reference levels after 50 months.

Sodium

Sodium concentrations in the reference streams ranged from 0.6 to 1.6 mg/l. A seasonal pattern was apparent: the higher concentrations usually were recorded in late summer and the lower concentrations in the spring. This pattern likely resulted from a dilution effect during spring snowmelt (Johnson et al. 1969). Following cutting, sodium concentrations rose steadily through the first 2 years to 3.0 mg/l in some cases (Fig. 5). In the spring of the fourth year after cutting, sodium, in all streams, decreased below reference levels for several months and then returned to reference levels.

Potassium

Potassium levels in the streams draining reference watersheds ranged from 0.1 to 0.7 mg/l, with most streams near 0.3. Following clearcutting, mean monthly concentrations ranged from 0.1 to 1.5 mg/l, with the average at 0.7 mg/l. However, on a paired-watershed basis, potassium concentrations were 3 to 4 times greater than reference levels following cutting, and they remained elevated throughout the study. There was neither an obvious second-year peak nor a gradual return toward reference levels during the 4 years (Fig. 5).

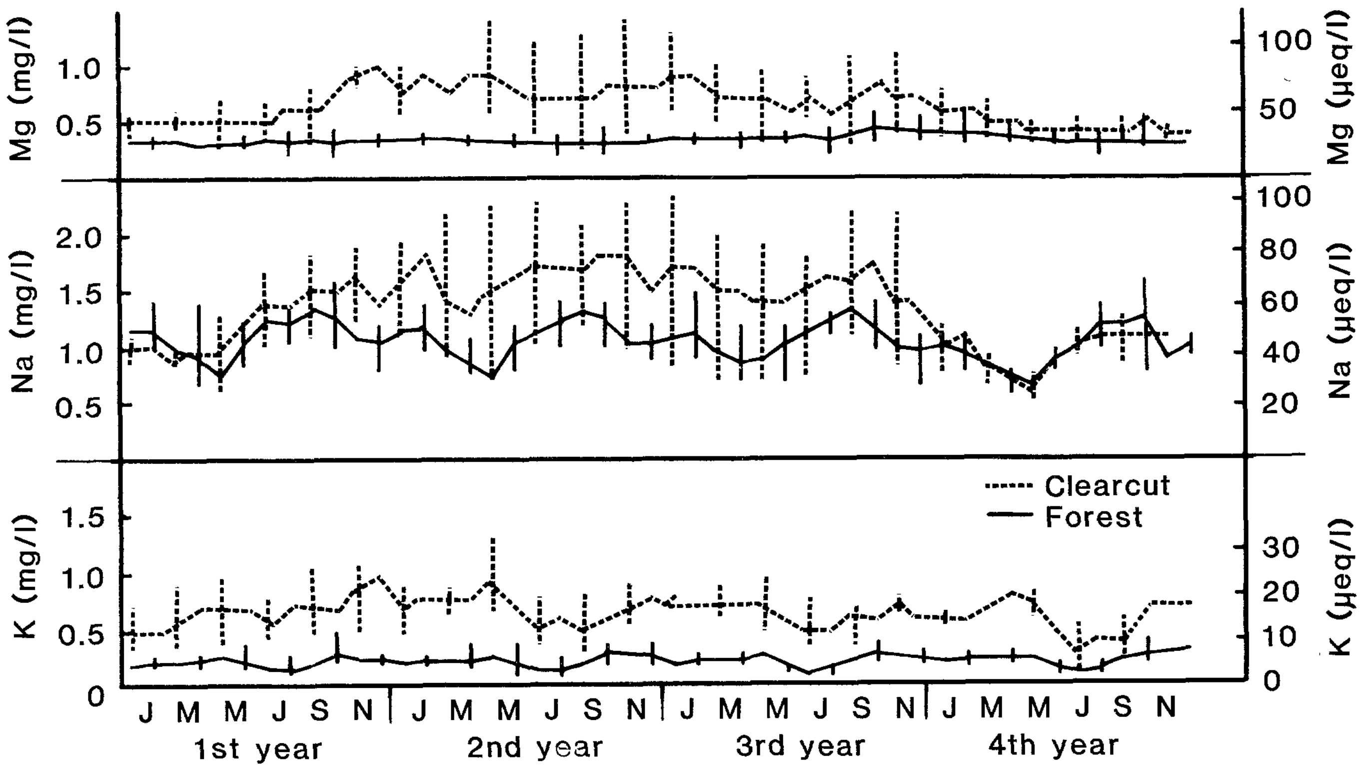

Figure 5.—Mean monthly magnesium, sodium, and potassium concentrations in several streams from both forested and clearcut watersheds for 4 years after cutting (vertical bars represent the range of mean monthly data among the individual streams studied).

Sulfate

Sulfate concentrations in the streams that drained both reference and clearcut watersheds were variable both among streams and from month to month in the same stream (Fig. 4). Sulfate in the streams that drained clearcut watersheds were below reference levels after cutting, and remained so throughout this study.

Chloride

During the first 2 years after cutting, average chloride concentrations from reference watersheds ranged from 0.3 to 0.6 mg/l. Those from the clearcuts ranged from 0.4 to 0.9 mg/l. During the third and fourth years after cutting, both reference and clearcut values ranged from 0.2 to 0.8 mg/l.

Downstream Concentrations

The stream system at Gale River provided us with an opportunity to compare dilution effects downstream from the clearcuts. A headwater stream was used as the forested reference. Samples were collected from several small streams that drained 100 ha that had been completely clearcut, and the data were averaged. Collections were also made downstream at points where the clearcutting represented 63, 17, 13, and 6 percent of the area of the watershed.

Only nitrate data are presented (Fig. 6) because that ion reacted most dramatically to clearcutting. These data indicate that the smaller the area of a watershed clearcut, the smaller the increase in concentration. Nitrate concentrations in streams from the watersheds with 13 and 6 percent of the area clearcut were not different from the reference values.

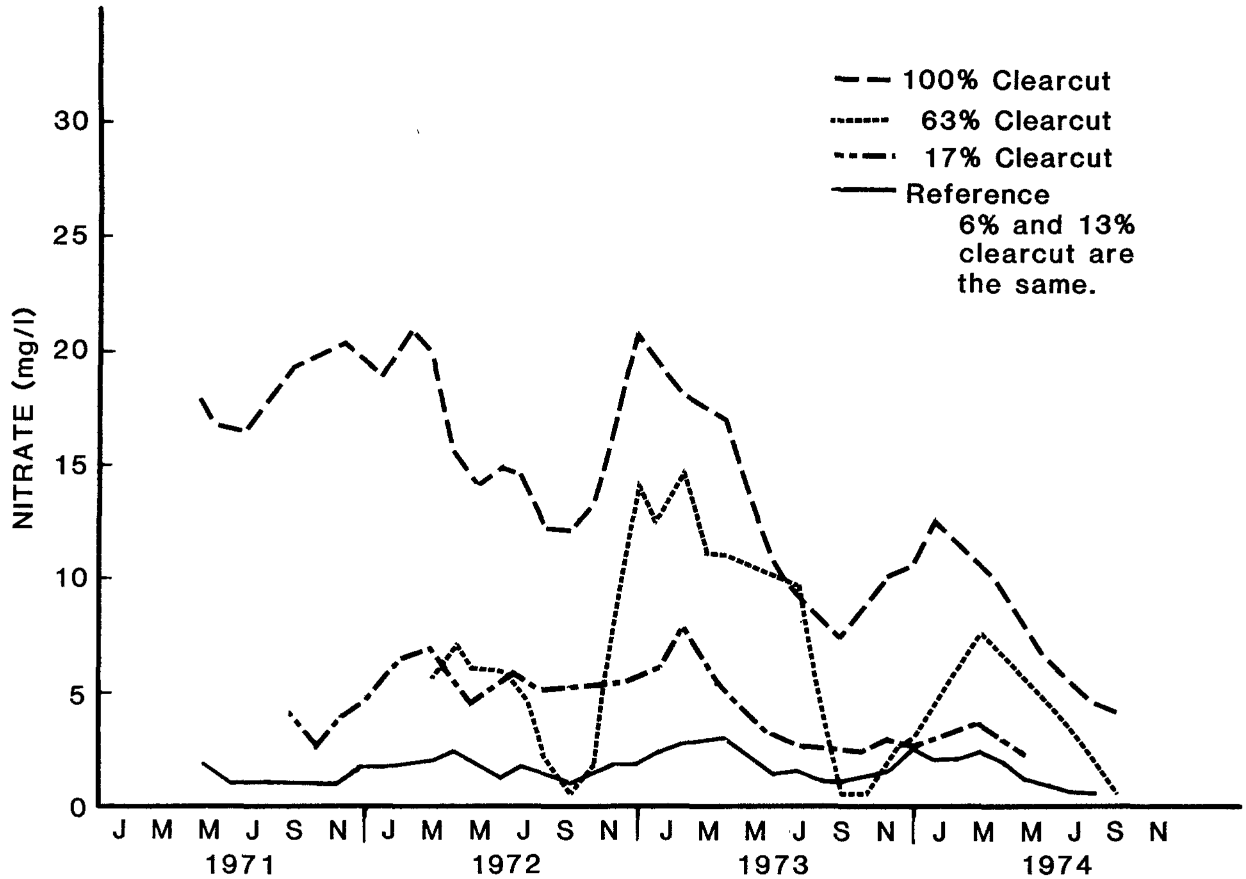

Figure 6.—Mean monthly nitrate concentrations in streams from an uncut, completely clearcut, and four partially clearcut watersheds. Data from the streams draining watersheds that were 13 and 6 percent clearcut were the same as from the reference.

Input-Output Nutrients Budgets

It is useful to know the total quantity of an element that has been removed from a watershed via streamflow. Nutrient flux values are presented to indicate the mass inflow and outflow of ions per hectare of watershed per year (Table 2). Losses of nutrients in particulate matter due to erosion were not considered, but are likely to have been small (Bormann et al. 1974).

Dissolved inorganic nitrogen (NO_3-N plus NH_4-N) in precipitation averaged 7.5 kg/ha/yr (Table 2) over the 2-year period. The reference watersheds lost 3.7 kg/ha/yr in streamwater for a net gain of 3.8 kg/ha/yr of inorganic nitrogen. This net gain compared favorably with the long-term mean of 2.5 kg/ha/yr observed for forested watersheds at Hubbard Brook from 1963 to 1974 (Likens et al. 1977).

Watersheds that had been clearcut for 1 year lost 2.2 times as much inorganic nitrogen as entered in precipitation. Losses the second year after cutting were 4 times greater than inputs. The net loss of inorganic nitrogen over the 4-year period was 42 kg/ha. For the same period, the reference watersheds were accumulating 15 kg/ha N (Table 2). On the basis of precipitation inputs and streamflow outputs only, by the fourth year after cutting, inorganic nitrogen was beginning to accumulate in the harvested watersheds again by about 2 kg/ha/yr. Gaseous exchange of nitrogen was not considered.

Small quantities of the cations (Ca^{++} and K^{+}) entered the watersheds dissolved in precipitation, and relatively large quantities were lost from the reference watersheds (Table 2). The second year after cutting, cation losses from cutover watersheds were nearly 3 times those from the reference watersheds. Over the 4-year span, 61 kg/ha of additional calcium and 15 kg/ha of additional potassium were removed from the harvested watersheds than from the references in stream water.

Table 2.—Input-output budgets. Input data are ionic additions from precipitation only; output data from the references and the clearcuts are dissolved substance losses to streamwater

Item	Nitrate nitrogen	Ammonium nitrogen	Calcium	Potassium
	kg/ha/yr			
Input (precipitation)	5.4 (1.4)[a]	2.1 (0.5)	1.2 (0.3)	0.6 (0.2)
Output (references)	3.6 (1.9)	0.1 (0.1)	12.5 (4.3)	2.0 (0.7)
Output (clearcuts)				
1st year after cutting	16.6 (3.7)	0.1 (0.1)	30.4 (10.1)	5.8 (1.9)
2nd year after cutting	29.7 (4.6)	0.1 (0.1)	32.9 (4.3)	5.7 (2.0)
3rd year after cutting	19.8 (8.4)	0.2 (0.1)	29.8 (9.2)	5.2 (1.9)
4th year after cutting	5.0 (3.3)	0.2 (0.1)	17.8 (3.0)	6.0 (2.0)

Item	Inorganic nitrogen[b]	Calcium	Potassium
	kg/ha		
	4-YEAR SUMMARY		
Inputs minus outputs (references)	+15.2	− 45.2	− 5.6
Input minus output (clearcuts)	−41.7	−106.1	−20.3
Net change (references minus clearcuts)	−56.9	− 60.9	−14.7

[a] Standard error.
[b] Nitrate plus ammonium.

Discussion

Clearcutting northern hardwood ecosystems sets in motion complex hydrological, biogeochemical, and ecological changes. Removal of the forest canopy: (1) increases soil temperature; (2) reduces transpiration; (3) increases soil moisture and streamflow; (4) increases decomposition of organic matter; (5) increases mineralization and nitrification; and (6) increases exchange of ions in the soil (Bormann and Likens 1979; Likens et al. 1970; Federer and Gee 1974; Federer 1973; Hornbeck et al. 1970; Covington 1981; Dominski 1971).

These changes, in turn, trigger a complex array of vegetative growth responses so that cutover sites are revegetated quickly. Increases in water, nutrients, and temperature resulting from cutting are reduced quickly as vegetation regrows; within a few years, these variables approach precutting levels. However, nutrient uptake by vegetative growth is, at first, less than nutrient release by accelerated mineralization; consequently, nutrients are lost from some systems in drainage water (Bormann et al. 1974; Bormann and Likens 1979).

This study and that of Pierce et al. (1972) confirm the findings of experimental studies at Hubbard Brook (Likens et al. 1970; Pierce et al. 1970) that commercial clearcutting of northern hardwoods throughout the White Mountain region results in accelerated nutrient loss in drainage water. The general pattern of nutrient loss in drainage water shows a maximum in the second year after cutting, with a general decline to near reference levels by the fourth year. This pattern is similar to that seen in the experimentally deforested watershed, W2, at Hubbard Brook.

Not all ions followed the same patterns. Nitrate, calcium, magnesium, sodium, and chloride peaked in the second year and then declined to reference levels by the fourth year. Potassium showed no obvious second-year peak nor a gradual return to reference levels. Sulfate concentrations dropped well below reference levels after cutting but returned to reference levels during the fourth year.

Although the average pH values showed no distinct patterns of change during the first 2 years after cutting, comparisons of stream water pH for individual paired watersheds (cut versus reference) showed discernible differences—generally, acidity was greater immediately after cutting. This increase probably was due in part to increased nitrification, which caused the release of additional nitrate and hydrogen ions to the streams immediately after cutting (Bormann et al. 1968; Likens et al. 1969; Bormann and Likens 1979; Vitousek et al. 1979). While the implications of increased acidity to stream water biota are not fully understood, there is evidence that low pH mobilizes soil aluminum that can be leached to streams and that may be injurious to aquatic life (Johnson 1979; Hall et al. 1980; Driscoll and Likens 1982). Also, Eaton et al. (1973) and Hornbeck et al. (1977) have shown that the forest canopy plays a major role in neutralizing acidic precipitation during the summer in New Hampshire. Removal of the canopy by harvesting may contribute to the increased acidity of the streams during the first year after clearcutting (Fig. 2). Many forest streams in New Hampshire currently are marginal for trout production because of the low pH and high concentrations of aluminum. A further decrease in pH, even for short periods, may be detrimental.

There is no clear explanation for the gradual decrease in acidity for the clearcut watersheds during the third and fourth years.

Our data indicate that nitrate concentrations in streams draining watersheds clearcut during the growing season usually are higher than those in streams from watersheds cut during the dormant season (Table 3). However, both the watershed with the highest concentration of nitrate in the stream and the one with the least were cut in the dormant season.

Table 3.—Mean annual nitrate concentrations (± standard error) from three watersheds cut during the summer growing season and from three watersheds cut during the autumn dormant season

	Cut	
Year after cut	Growing season	Dormant season
	--------------*mg/l*-------------	
First	14.2 ± 4.0	11.3 ± 6.5
Second	20.4 ± 4.6	12.6 ± 6.9
Third	13.4 ± 5.2	6.3 ± 4.5

Nutrient concentrations in streams draining clearcuts decrease distinctly as the proportion of the watershed cut becomes smaller. Dilution occurs as water with low concentrations of nutrients enters the streams from uncut areas, either from tributary streams or from subsurface flow. Chemical reactions within the stream and nutrient assimilation by the organisms in the stream channel itself and in the bottom sediments may contribute to the reduction in nutrients with distance downstream (Sloane 1979). Whatever the reason, our data show that 10 to 15 percent of a watershed in the White Mountains could be clearcut without measurably affecting the nitrate and calcium levels in streamflow at the base of the watershed.

If it is desirable to clearcut larger proportons of a watershed, it would seem prudent to harvest in a series of small cuttings spaced at least 2 years apart. The 2-year spacing would minimize the synchronization of maximum nutrient loss the second year after cutting over large areas of a watershed (Hornbeck et al. 1975).

Our estimated losses of nutrients in streamwater from commercially cut northern hardwood forests are substantially less than from the experimentally devegetated watershed, W2, at Hubbard Brook (Table 2) (Likens et al. 1970; Pierce et al. 1972). Nevertheless, the amounts of nutrients lost are not insignificant. Over the 4 years after cutting, losses (net change for reference minus net change for cutover) of 57, 61, and 15 kg/ha for N, Ca^{++}, and K^{+} constitute about 70, 98, and 23 percent of the annual estimated uptake for these elements (Likens et al. 1977). Compared to the total amounts of these elements in the system, these losses are small, but it is not known how they compare to the actual proportion of the total that is available for use by the vegetation. Studies underway at Hubbard Brook suggest that losses of this magnitude will not reduce production substantially so long as sufficient time is allowed between cuts for the ecosystem to reaccumulate nutrients from the atmosphere, weathering, or biological fixation. At this time, the 100-year rotation in northern hardwood forests used by the USDA Forest Service seems ample. However, repeated short rotations might ultimately prove deleterious to future productivity.

Conclusions

1. Clearcutting of northern hardwood forests on glacial till throughout northern New Hampshire resulted in a response similar to that of experimentally clearcut watersheds at Hubbard Brook. Substantial quantities of nutrients were lost in drainage water during a 4-year period after cutting.
2. Conductivity of the streams draining clearcuts more than doubled during the second year after cutting but returned to reference levels during the fourth year.
3. Streams became slightly more acidic during the first year after clearcutting; however, during the third and fourth years after cutting, the streams were substantially less acidic than the references. Greater acidity may have adverse consequences for fish and invertebrates in streams that are marginal habitats with respect to pH levels before cutting.
4. Concentrations of nitrate nitrogen, calcium, magnesium, sodium, and potassium increased substantially in the streams from the clearcuts during the first 3 years after cutting, representing losses of these plant nutrients from the forest soils to streams.
5. Concentrations of sulfate decreased in streams draining the clearcuts during the first 3 years after cutting.
6. Clearcutting seemed to have almost no effect on the concentrations of chloride and ammonium nitrogen.
7. All ions except hydrogen and potassium returned to reference levels in the streams from the clearcuts. By the end of the fourth year after cutting, there were considerably fewer hydrogen ions and considerably more potassium ions in the streams from harvested areas than in those from the reference areas with no indicaton of impending recovery.
8. Concentrations of ions in streamwater were diluted in proportion to the area of the watershed clearcut. Clearcutting about 15 percent of a watershed did not measurably change the chemistry of the major streams in the watershed.
9. Clearcutting during the dormant season affected stream chemistry less than harvests during the growing season.
10. During the 4 years of study, the clearcut watersheds lost 57 kg/ha of inorganic nitrogen, 61 kg/ha of calcium, and 15 kg/ha of potassium in streamflow. This loss does not include losses in forest products removed, accelerated denitrification, or gains due to fixation, which were not measured.

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Commercial clearcutting of northern hardwood forests changed the chemistry of the streams that drained from them. By the second year after cutting, specific conductance doubled, nitrate increased tenfold, calcium tripled, and sodium, magnesium, and potassium doubled. Chloride and ammonium did not change; sulfate decreased. Concentrations of most ions returned to reference levels after 4 years, though sulfate remained depressed, potassium remained elevated, and acidity decreased.

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