United States
Department of
Agriculture

Forest Service

**Northeastern Forest
Experiment Station**

NE-RP-596

The Northern Hardwood Forest Ecosystem: Ten Years of Recovery from Clearcutting

J. W. Hornbeck
C. W. Martin
R. S. Pierce
F. H. Bormann
G. E. Likens
J. S. Eaton

Abstract

Two even-age management systems, progressive strip cutting and block clearcutting, have been studied since 1970 on small watersheds at the Hubbard Brook Experimental Forest, New Hampshire. In the strip cutting, all merchantable trees were harvested in a series of three strips over 4 years (1970–74). In the block clearcutting, all trees were harvested in a single operation in 1970. This paper contrasts progressive strip cutting and block clearcutting for the 10-year period after initiation of harvest in terms of hydrologic response, erosion losses, stream water ions, nutrient leaching, nutrient removals in harvested products, and natural regeneration of vegetation.

The Authors

J. W. HORNBECK, C. W. MARTIN, and R. S. PIERCE are with the Northeastern Forest Experiment Station, Durham, New Hampshire. F. H. BORMANN is with Yale University's School of Forestry and Environmental Studies, New Haven, Connecticut. G. E. LIKENS and J. S. EATON are with the Institute of Ecosystem Studies, The New York Botanical Garden, The Mary Flagler Cary Arboretum, Millbrook, New York.

Manuscript received for publication 25 March 1986

Northeastern Forest Experiment Station
370 Reed Road, Broomall, PA 19008
February 1987

COVER—Harvested watersheds at the Hubbard Brook Experimental Forest in New Hampshire.

Contents

Introduction

Northern hardwood forests in the Northeastern United States provide highly valued goods and services, including timber, recreation, esthetics, wildlife, and watershed protection. Because these products cannot always be obtained simultaneously, controversy sometimes arises over how best to use the resources of the northern hardwood forest.

The best known example is the conflict over the use of clearcutting for harvesting northern hardwoods (Horwitz 1974). Clearcutting is defined as the harvesting in one cut of all trees on an area for the purpose of creating a new, even-aged stand (USDA 1973). For forest managers, clearcutting is an attractive silvicultural method because it is economical and amenable to the increasing mechanization accompanying harvests, and it favors new stands with high proportions of commercially valuable species of *Betula* and *Acer*. On the other hand, since the late 1960's there has been an increased awareness of possible adverse effects of clearcutting on soil nutrients, water quality, wildlife, esthetics, and stand regeneration.

Some of the concerns about clearcutting have eased. Forest managers addressed the problem of esthetics by making clearcuts smaller, cleaning up debris to improve the appearance of the harvest site, and locating boundaries of cut areas to fit the landscape. But other concerns, such as those regarding soil nutrients, hydrology, and stand regeneration, could not be addressed adequately, and stimulated new research. This paper is an example, reporting research begun in 1970 at the height of the concerns over clearcutting. The study involves two types of clearcutting in northern hardwoods, block and progressive strip, and how each affects nutrient and hydrological cycling and stand regeneration. The results span 10 years, or from harvest well into the establishment of new stands.

Progressive strip cutting evolved from block clearcutting as an attempt to further favor regeneration of birches by more closely controlling variables such as distance to seed sources, light, moisture, and scarification of the seedbed. The method of strip cutting applied in our study is recommended by Marquis (1966) and Safford (1983) and entails cutting strips about 25 m wide oriented along the contour with 50–m–wide uncut strips between them. After a 2-year period for establishment of regeneration, a second series of 25–m strips are cut on the southernmost or westernmost side of the original cut. The remaining strips are then cut after a second establishment period of 2 years. As in block clearcutting, all merchantable stems are removed and scarification is encouraged during logging, with appropriate measures to avoid erosion (Marquis 1969; Filip 1969).

After the first strip is cut, it receives shade from the trees on its south or west border. This provides favorable conditions for germination and early survival. When the second strip is cut, it receives shade for initial establishment but also allows the first strip to receive direct sunight. Thus, both the first and second strips receive shade for seedling establishment, and then direct sunlight for best growth. During these harvests, seed sources are close by in the uncut strips. When the third strip is cut, it receives only minimal shade, and seed sources are more distant. However, *Betula* and *Acer* seedlings that survive the first year or two of direct sunlight then have optimal growing conditions in terms of light and moisture.

By stretching over 4 years, strip cutting would seem to lessen some of the environmental concerns surrounding block clearcutting. The strips of varying ages of living vegetation minimize erosion and leaching of nutrients to streamflow. However, testing is needed to determine if advantages of strip cutting in terms of stand regeneration and protection of site and stream water outweigh the convenience and economics of block clearcutting. Our study addresses some of these questions.

The Study Area

Our study was conducted on the 3,000-ha Hubbard Brook Experimental Forest in West Thornton, New Hampshire. Hubbard Brook is operated by the USDA Forest Service's Northeastern Forest Experiment Station. Four small watersheds were used: watershed 6, an untreated control for the nutrient cycling studies, is 13 ha; watershed 3, an untreated control for the hydrologic studies, is 42 ha; watershed 4, which was strip cut, is 36 ha; and watershed 101, which was clearcut as a block, is 12 ha (Fig. 1). The watersheds extend from 450 to 800 m above sea level and have southerly aspects and average slopes of 20 to 30 percent.

Descriptions of the study sites have been given in previous publications of the Hubbard Brook Ecosystem Studies. Vegetation has been described by Bormann et al. (1970) and Siccama et al. (1970). The biogeochemistry is described in Likens et al. (1977), and the hydrology and climate in Hornbeck et al. (1970). Soils on the study watersheds are derived from coarse-textured, glacial till material that has been subjected to frost action, erosion, and deposition since glacial retreat about 14,000 years ago. Till depths range from 0 to 5 m. The surficial layers have weathered to form fine sandy loams classed as Lithic and Typic Haplorthods. Soil profiles often are mixed due to treethrow, but usual development includes O, E, Bhs, Bs, and C horizons that differ markedly in physical and chemical properties. Soil depths average 0.5 m on top of a dense basal till nearly impermeable to roots and water. The more common soil series include Marlow, Lyman, Peru, Hermon, and Monadnock.

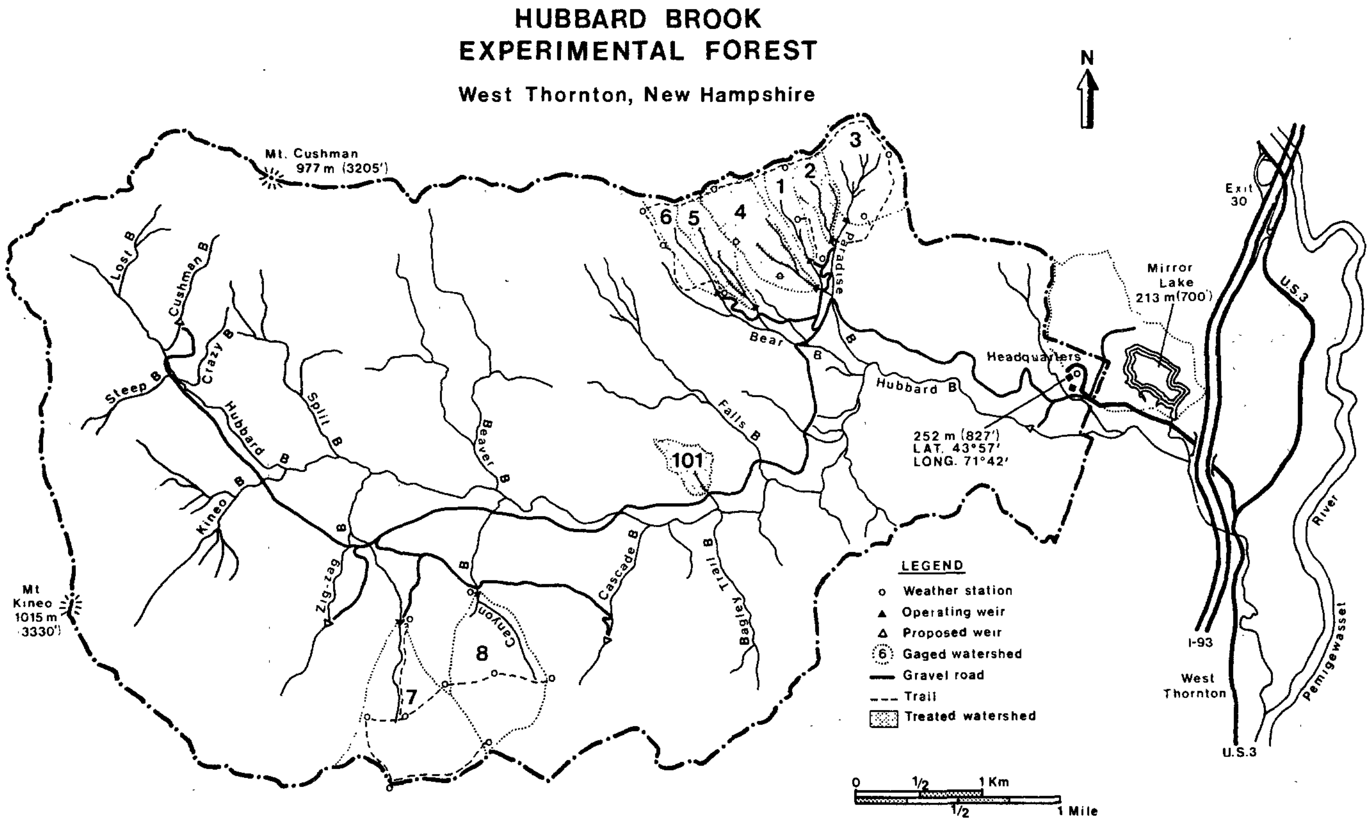

Figure 1.—The Hubbard Brook Experimental Forest and location of study watersheds 3, 4, 6, and 101.

Design and Methods

Watershed Harvests

In preparation for harvest, watershed 4 was surveyed into 49 strips, each 25 m wide. The strips were oriented from east to west roughly parallel to watershed contours. Harvests were done in the autumn months, generally a favorable time for minimizing logging disturbance. The first series of strips was harvested from September 28 to October 29, 1970, the second series from September 7 to October 1, 1972, and the third series from October 1 to November 1, 1974 (Fig. 2). A variable-width buffer strip of uncut trees, from 15 to 25 m wide, was left on both sides of the major stream channel to minimize solar heating and sedimentation of streams.

The block clearcut on Watershed 101 (Fig. 3) was carried out from October 30 to November 28, 1970, or immediately after harvest of the first series of strips. No streamside buffer strip was left during the block clearcutting.

On both the strip cut and block clearcut, all trees and snags more than 2.5 cm in d.b.h. were felled. Merchantable tree boles as determined by the operator were transported by rubber-tired skidders to landing areas adjacent to the base of the harvested watersheds. Tops and branches were left on site, but were moved if they fell in stream channels. Main skidder trails were laid out generally along ridges, well away from streams in accordance with USDA Forest Service specifications. Culverts were used at stream crossings and water bars were placed on skid trails immediately after completion of logging. Skidder operators were encouraged to vary their routes to provide scarified conditions necessary for successful germination and growth of birch seed. In general, every effort was made to perform an ecologically sound logging operation that would encourage regeneration yet minimize damage to forest soils and streams.

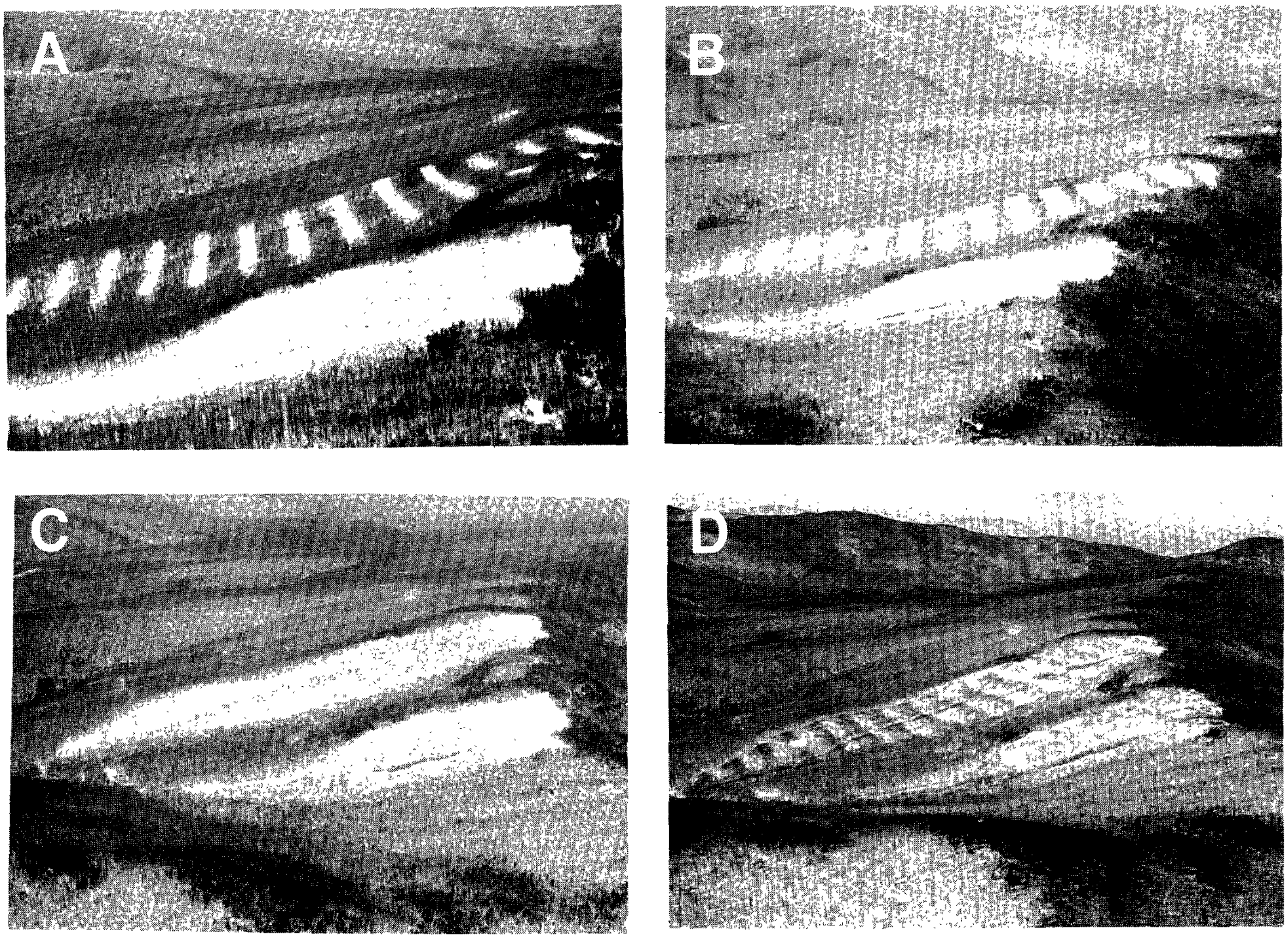

Figure 2.—East to west views across strip-cut watershed showing: (A) first strip cut; (B) first and second strips cut; (C) all strips cut; (D) regeneration at 10 years after initial harvest. Cleared area in foreground is an earlier deforestation experiment on Hubbard Brook watershed 2 (see Pierce et al. 1970).

Hydrology Studies

Volume of precipitation is sampled by a network of standard and recording gages that have a density of one gage per 15 ha of watershed area. Streamflow from watershed 3, the control for the hydrology studies, and from watershed 4, the strip-cut watershed, is measured continuously with 120° V-notch weirs (Reinhart and Pierce 1964). Streamflow from watershed 6, the control for the nutrient cycling studies, is measured with a tandem 60-cm-wide flume and a 90° V-notch weir. A water year of June 1 through May 31 is used for summarizing and analyzing hydrologic data at Hubbard Brook (Likens et al. 1977).

Effects of the strip cutting on water yield have been determined using the control watershed concept. For 9 years before treatment, streamflow values from watershed 4 and control watershed 3 were used to develop linear regression equations between the two watersheds. Separate regressions were prepared for various streamflow values, including monthly, seasonal, and annual totals. After strip cutting, streamflow values from watershed 3 (the control) were used in the equations to determine what the streamflow values would have been for watershed 4 had it not been strip cut. As an example, the water year equation is:

Estimated flow
from watershed 4 = 1.54 + 1.03 (flow from control)

A difference in streamflow between the actual watershed 4 measurement and the estimated flow for the same watershed was considered statistically significant and was attributed to strip cutting if the deviation exceeded the 95 percent confidence interval about the regression line.

Watershed 101, the site of the block clearcutting, does not have a stream gage. Instead, daily streamflow was simulated using BROOK, a hydrologic model developed and tested on forested watersheds at Hubbard Brook and also tested at other locations (Federer and Lash 1978a,b). The decision to use simulation rather than a gaged watershed was based on three factors: (1) remaining gaged watersheds at Hubbard Brook were needed for future studies, (2) earlier studies have successfully demonstrated the use of hydrologic simulation (Sollins et al. 1980; Leaf and Alexander 1975), and (3) hydrologic models have become sophisticated and tests show that they are capable of highly accurate estimates of measured streamflow (Singh 1982). Regarding the last point, we tested BROOK by simulating several years of pre- and post-harvest streamflow from the strip-cut watershed. Monthly sums of simulated daily flows were within ± 3 percent of measured flow except for a few summer months which had total flows of less than 0.5 cm. Thus the capability of the BROOK model to simulate streamflow usually is within the 3- to 5-percent error range associated with stream gaging (Hornbeck 1965).

Inputs required to run BROOK, including daily air temperature and precipitation, were collected at watershed 6 about 1.5 km to the east. Various parameters used in the model, such as leaf area index, stem area index, and depth of the rooting zone, were adjusted to simulate flow during the postharvest period. Streamflow was simulated for the same period using parameters for an undisturbed forest. Differences in streamflow for the two simulations were attributed to harvest.

Erosion Losses in Streamflow

Erosion and resulting losses of organic and inorganic particulate matter in streamflow are extremely difficult to quantify for forests. Fortunately, erosion usually is not serious in undisturbed northern hardwood forests; with proper precautions, it can be controlled during and after harvests (Patric 1976; Patric et al. 1984). In our study, care was taken to minimize erosion. However, to ensure that a large increase of eroded material and associated nutrients did not go undetected, we periodically measured material trapped in the weir basins, and also sampled stream turbidity, a commonly used index of suspended material.

Weir basin data. Eroded material can leave the watershed in particulate form, either as suspended load transported by turbulent water or as bedload moving along the bottom of the stream channel. As streams leave the watershed, velocity is slowed by the weir basins, and heavier particulate matter settles out. The weir basins for the control and strip-cut watersheds have been cleaned, and oven-dry weights of the material removed have been obtained on an annual basis since 1965.

Turbidity data. Suspended particulate matter that normally would not settle in the weir basin was sampled by turbidity measurements. Grab samples were obtained periodically during nonstorm periods and during most storm events. Sampling was continued for 6 years after initiation of the strip cutting and for 3 years after block clearcutting. The longer interval for the strip cutting was needed to span the three separate harvests.

Samples were analyzed with an electronic turbidimeter and results expressed as Jackson Turbidimeter Units (JTU). A value of less than 1 JTU represents clear water while a value of several hundred JTU represents a large amount of suspended material. Turbidity cannot be used to quantitatively express erosion losses, but turbidity values do indicate whether sizeable amounts of eroded materials are reaching the stream channel and leaving the watershed.

Stream Water Ions and Nutrient Budgets

Details of methods used in collecting and analyzing stream samples are given in Likens et al. (1977). Briefly, weekly grab samples were collected just above the weirs on watersheds 4 and 6 since 1963, and at the lower boundary of

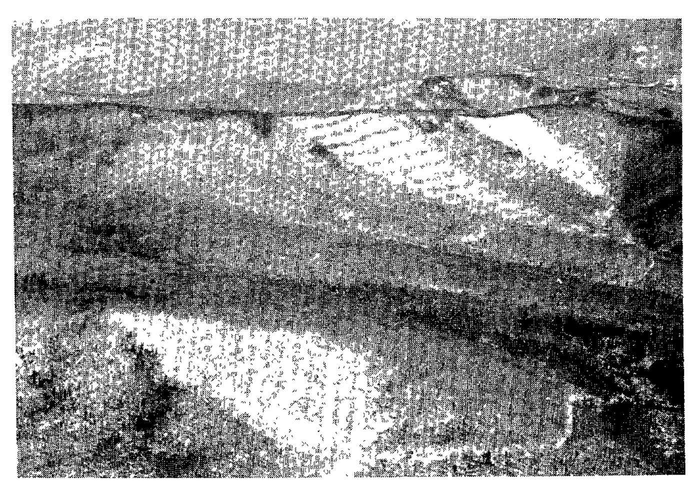

Figure 3.—Block clearcut is in foreground. Strip cut and an earlier deforestation experiment are at upper right.

watershed 101 since 1969. The samples were returned to the laboratory and analyzed for pH, specific conductance, and chemical ions, including Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, SO_4^{2-}, NO_3^-, and Cl^-. THe pH was determined potentiometrically, the anions and NH_4^+ by automated colorimetric analysis, and the cations by atomic absorption; PO_4^{3-} was measured during part of the study, but usually was below the detection level of 0.003 mg L^{-1}. Effects of harvest on stream water ions usually were obvious, and were easily demonstrated with graphs. We plotted mean monthly concentrations obtained by weighting individual weekly values for volume of streamflow, and then averaging over the month.

Nutrient budgets were determined by converting the ionic concentrations of precipitation and streamflow to inputs and outputs as mass per unit area. Daily inputs and outputs are calculated as the product of the ionic concentration (mg L^{-1}) in the weekly sample times volume (L) of water for each day represented by the sample. The same regression technique described for water yield studies was used to determine effects of harvest on nutrient outputs.

Biomass and Nutrients in Harvested Products

During harvest, pulpwood and sawlogs were scaled at landings located at the base of the strip-cut and block-clearcut watersheds. The scale data were converted to solid cubic volume by a formula for truncated cones. Constants developed at Hubbard Brook by Whittaker et al. (1974) were applied to convert the volumes to oven-dry weight of biomass in bark, heartwood, and sapwood. Nutrient contents of these three components are available from chemical analyses of plant tissues made at Hubbard Brook (Likens and Bormann 1970). The estimate of nutrient removal in kg ha^{-1} was obtained by multiplying biomass by percent nutrient content for elements of interest.

Regeneration

Regeneration on the block-clearcut and strip-cut watersheds has been surveyed on permanent plots at intervals of 1 to 3 years since harvest. Detailed results will be reported in a separate paper, but a summary of regeneration at years 2 and 10 after harvest is included in this paper. The summary is based on surveys of fifty-seven 25 by 25-m plots on the strip cut, and forty-eight 25 by 25-m plots on the block clearcut. Plots on the strip cut were chosen randomly after stratification by elevation and year cut. Plots on the block clearcut were chosen at random with no stratification since the harvest was completed in a single operation and the elevation range of the entire harvest area was about the same as for the mid-elevation plots on the strip cut.

A nested design was used for sampling each plot. The entire 25 by 25-m plot was used to sample trees more than 10 cm in d.b.h. Trees between 2 and 10 cm d.b.h. were tallied on a 1 by 25-m strip running the length of either the east or west side (decision by coin toss) of each plot. Lesser vegetation was surveyed on four 1-m^2 subplots spaced evenly along the 1 by 25-m strip plot. Within each of these subplots, stem counts were made by species for trees, shrubs, and herbs less than 0.5 m tall and for those more than 0.5 m tall. Visual estimates of percent of plot covered were used in place of stem counts for grasses, sedges, rushes, and mosses. Data from the subplots were averaged to give stems per m^2 for each 1 by 25-m strip.

Estimates of aboveground biomass of regeneration were obtained by establishing 46 additional plots on the strip-cut watershed, stratified by elevation and year cut. On these plots, individual species were clipped, grouped according to height or d.b.h. class, and oven dried at 105°C. Stem counts for individual species from the regeneration survey were multiplied by corresponding oven-dry weights to obtain biomass estimates on a kg ha^{-1} basis.

Results

Hydrologic Response

Strip cutting. Removal of the forest by strip cutting caused streamflow to increase in the 4 water years spanning harvest and for 3 additional years (Table 1). The annual increases ranged from 22 to 114 mm. The minimum value occurred the first year after the first set of strips was harvested, and coincided with below-average precipitation (Table 1). The maximum value occurred with two-thirds of the watershed harvested and coincided with an annual precipitation that exceeded the long-term average by 40 percent. Above-average precipitation is recognized as necessary for optimum increases in streamflow from deforested areas (Douglass and Swank 1972). Increases or decreases in water yield were statistically significant in 9 of the 10 years after harvest, and totaled 397 mm or 4 percent more than would have occurred if the watershed had not been harvested. Over three-fourths of this increase occurred in the first 5 years, or while the watershed was in the process of being harvested.

Most of the annual increase occurred during the growing season (Table 1). Thus, streamflow increases resulted primarily from a reduction in transpiration and canopy interception rather than from increased snow accumulation within the strips. As further evidence, changes in streamflow for the dormant season (October through May) and the period of major snowmelt runoff (March 1 through May 15) usually were small and not statistically significant (Table 1).

Table 1.—Streamflow and precipitation for strip-cut and block-clearcut watersheds, in millimeters (cutting on both watersheds began in 1970)

	Streamflow, strip-cut watershed			Streamflow, block-clearcut watershed			Precipitation	
Year after cutting	Estimate if uncut	Actual	Change due to cutting	Simulated for uncut	Simulated for cut	Change due to cutting	Actual	Departure from 23-year mean
			WATER YEAR (JUNE-MAY)					
1[a]	776	798	+22*	769	1046	+278	1222	−84
2[a]	1032	1078	+46*	1007	1163	+155	1505	+199
3[b]	1417	1531	+114*	1363	1455	+92	1833	+527
4[b]	819	886	+67*	777	816	+39	1239	−67
5[c]	1263	1318	+55*	1221	1260	+41	1659	+353
6[c]	868	949	+81*	876	896	+20	1323	+17
7[c]	973	1042	+69*	1031	1046	+15	1431	+125
8[c]	884	870	−14	888	893	+8	1286	−20
9[c]	755	725	−30*	743	744	+1	1138	−168
10[c]	796	769	−27*	844	840	+4	1261	−45
Total	9583		411	9519		653		
			GROWING SEASON (JUNE-SEPT)					
1[a]	52	80	+28*	46	208	+237	402	−44
2[a]	156	192	+36*	114	254	+140	487	+44
3[b]	368	459	+91*	324	409	+85	703	+257
4[b]	139	177	+38*	98	143	+45	519	+73
5[c]	217	298	+81*	196	232	+36	611	+165
6[c]	100	138	+38*	77	99	+22	489	+43
7[c]	80	107	+27*	108	118	+10	489	+43
8[c]	91	93	+2	84	90	+6	316	−130
9[c]	57	63	+6	58	63	+5	379	−67
10[c]	31	31	−0	30	35	+5	382	−64
Total			347			592		
			DORMANT SEASON (OCT-MAY)					
1[a]	759	755	−4	748	756	+8	773	−87
2[a]	724	719	−5	725	766	+41	820	−40
3[b]	873	887	+14	894	909	+15	1018	+158
4[b]	1038	1071	+33	1039	1046	+7	1130	+270
5[c]	676	709	+33	680	674	−6	720	−140
6[c]	1041	1019	−22	1024	1029	+5	1048	+188
7[c]	766	800	+34	876	896	+20	834	−26
8[c]	893	935	+42*	1031	1046	+15	942	+82
9[c]	792	777	−15	888	893	+5	970	+110
10[c]	697	662	−35	743	744	+1	759	−101
Total			77			110		

Continued

Table 1.—Continued

Year after cutting	Streamflow, strip-cut watershed: Estimate if uncut	Actual	Change due to cutting	Streamflow, block-clearcut watershed: Simulated for uncut	Simulated for cut	Change due to cutting	Precipitation: Actual	Departure from 23-year mean
				SNOWMELT (MARCH 1-MAY 15)				
1[a]	472	473	+1	503	502	-1	d	
2[a]	515	510	-5	478	470	-8	d	
3[b]	461	489	+28	471	450	-21	d	
4[b]	454	459	+5	594	576	-18	d	
5[c]	402	421	+19	318	312	-6	d	
6[c]	496	491	-5	521	496	-25	d	
7[c]	463	485	+22	473	476	+3	d	
8[c]	336	347	+11	470	469	-1	d	
9[c]	595	572	-23	571	554	-17	d	
10[c]	340	325	-15	301	296	-4	d	

* Significant at 0.05 level of probability.
[a] One-third of strip-cut watershed harvested.
[b] Two-thirds of strip-cut watershed harvested.
[c] Entire strip-cut watershed harvested.
[d] Precipitation for this period not related to streamflow.

Although strip cutting did not change the volume of snowmelt runoff, it did affect timing. With reduced shade after harvest, snow melted more quickly and snowmelt runoff was advanced. In monthly analyses (Fig. 4), this effect shows as an increase in streamflow for March or April, the first month of major snowmelt. Decreases in streamflow then occur in 1 or 2 following months, while in undisturbed watersheds, snowmelt progresses at the usual speed. The increases and decreases during snowmelt months balance closely.

Block clearcutting. On the basis of streamflow simulation, block clearcutting caused streamflow to increase by 278 mm, or 36 percent in the first year after harvest (Table 1). The increases tapered off rapidly with revegetation, and annual streamflow was nearly like the control watershed by the sixth year of regrowth. Total increase in streamflow for the 10-year period of study was 653 mm, or 7 percent more than if the watershed had not been harvested. As with the strip cutting, most of the annual increase occurred in the growing season (Table 1). Snowmelt runoff was advanced slightly more than on the strip cut due to the absence of uncut strips.

Erosion Losses

For the 6 years before harvest, erosion losses measured as material trapped in the weir basins averaged 33.6 ± 17.2 kg ha^{-1} for the control watershed and 40.4 ± 25.1 kg ha^{-1} for the strip cutting. Averages for the 10-year postharvest period were 37.7 ± 10.8 kg ha^{-1} for the control watershed and 36.7 ± 28.7 kg ha^{-1} for the strip cutting. Thus, strip cutting did not result in any important changes in amounts of material leaving the watershed as bedload or heavy particulate matter.

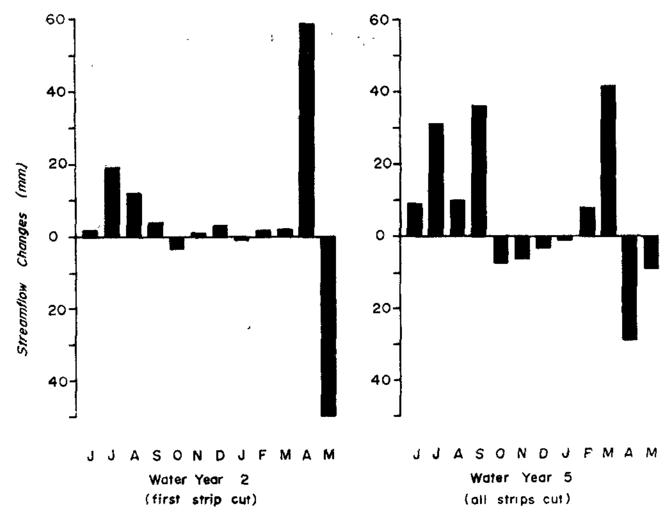

Figure 4.—Change in streamflow, by month, for 2 selected years after strip cutting.

The conclusion is the same for suspended materials as determined by turbidity measurements. During and after harvest, 325 samples were collected for turbidity analysis from both the control and strip cut, and 160 samples were collected from the block clearcut. A summary of these samples by turbidity class is shown in Table 2. About one-half of the samples were collected during storm events and should represent maximum effects of harvest.

The 11 samples falling in the 11–40 JTU class probably are the result of logging disturbances, especially since no corresponding values occurred for the control watershed. A more important point is that turbidity values remained quite low and exceeded 1 JTU on few occasions.

Stream Water Ions

Calcium. Before harvest, concentrations of Ca^{2+} averaged about 2 mg L^{-1} on the strip-cut watershed and just over 1 mg L^{-1} on the control and block-cut watersheds (Fig. 5). The concentrations were fairly stable throughout the year, and there were no obvious seasonal patterns.

Strip cutting caused Ca^{2+} to increase slightly, mostly during the dormant seasons (Fig. 5). The best example was in the dormant season 1 year after harvest of the first strip when Ca^{2+} was increased by an average of 0.8 mg L^{-1}. The increases were smaller in subsequent dormant seasons, even with cutting of the second and third sets of strips.

Table 2.—Number of samples collected for post-harvest turbidity analysis

Item	Jackson Turbidimeter Units			
	⟨1	1-5	6–10	11–40
Control				
Nonstorm periods	175	3	0	0
Storm events	143	4	0	0
Total	318	7	0	0
Strip cut				
Nonstorm periods	171	2	2	3
Storm events	130	9	2	6
Total	301	11	4	9
Block clearcut				
Nonstorm periods	52	5	1	1
Storm events	88	10	2	1
Total	140	15	3	2

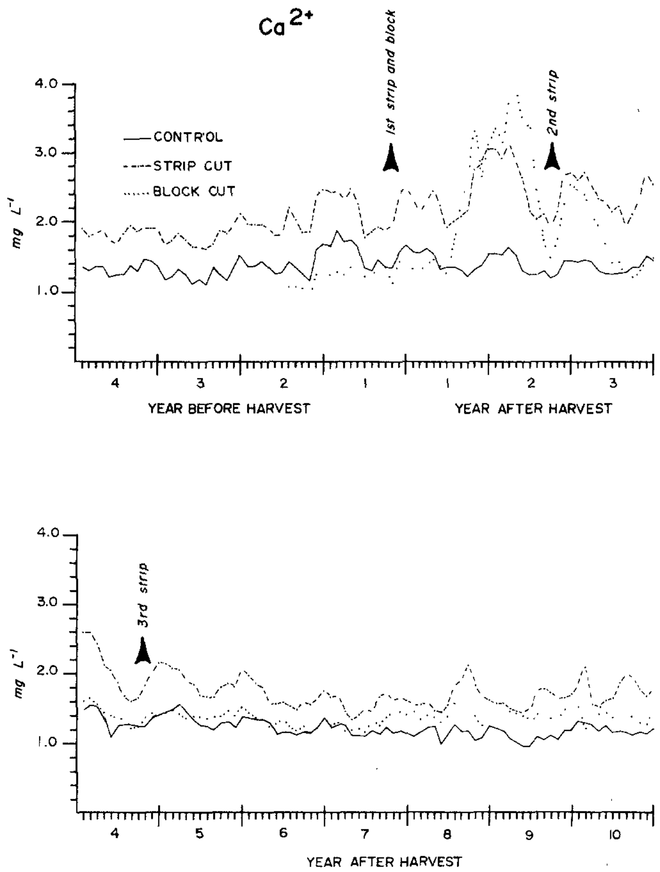

Figure 5.—Weighted, mean monthly Ca^{2+} in stream water, by calendar year.

The block cut caused a similar pattern. Effects were greatest in the dormant season 1 year after harvest; Ca^{2+} concentrations from the block cut exceeded values for the control watershed by about 3 mg L^{-1} (Fig. 5). The effects of block cutting then declined gradually and were minimal by the end of the third year after harvest.

Potassium. Preharvest levels of K^{+} averaged 0.2 mg L^{-1} for the study watersheds (Fig. 6). A seasonal pattern of low values in summer and a rise to higher concentrations in winter is correlated with vegetation activity (Johnson et al. 1969). Potassium concentrations for the strip-cut watershed increased immediately after cutting and on average were about 0.1 mg L^{-1} higher than on the control during the 2 years after the first strip cut; 0.2 to 0.3 mg L^{-1} higher after the second sets of strips was cut; and 0.3 to 0.6 mg L^{-1} higher after the third set was cut. As with Ca^{2+}, the treatment effect was greatest in the dormant season. Unlike Ca^{2+}, the increases have persisted and the maximum

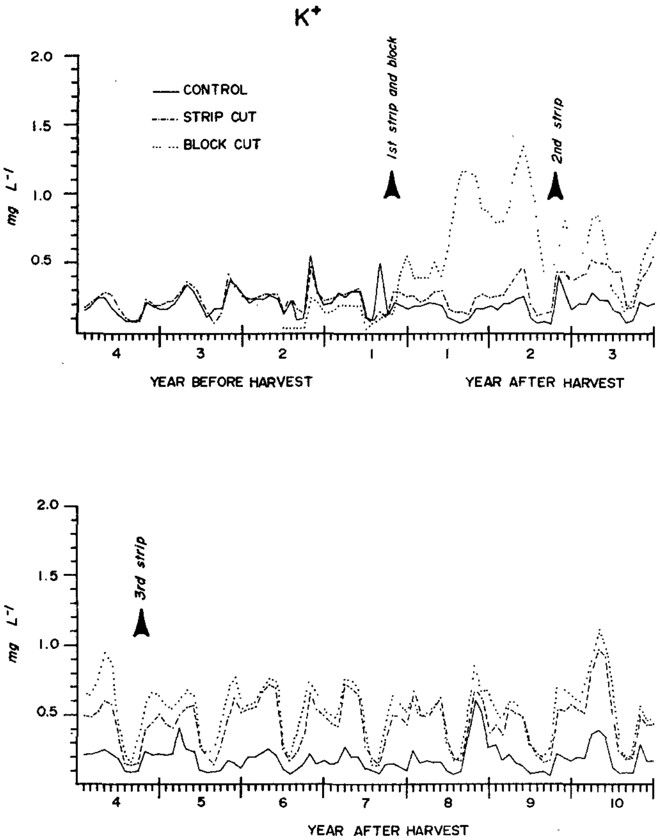

Figure 6.—Weighted, mean monthly K^+ in stream water, by calendar year.

increase of 0.6 mg L^{-1} occurred in April of the 10th year after harvest.

Potassium concentrations also responded immediately to block clearcutting. By the end of the second dormant season they were 5 times higher from the block clearcutting than from the control watershed (Fig. 6). Concentrations have declined since then, but the effects of cutting remain evident through the 10th year of regrowth.

Magnesium. Magnesium in stream water averaged about 0.4 mg L^{-1} before harvest and did not fluctuate with season or discharge. Effects of harvest occurred at the end of the first summer after cutting; there was an increase of 0.2 mg L^{-1} on the strip cut and 0.5 mg L^{-1} on the block cut. The increases persisted at declining levels for 1 1/2 years on the block cut. There were increases of less than 0.1 mg L^{-1} on the strip cut until 1 year after the final set of strips was harvested.

Sodium. Before harvest, Na^+ concentrations were fairly stable at about 1 mg L^{-1}, though peaks of up to 2 mg L^{-1} sometimes appeared in late summer. In the first 5 years after the start of strip cutting, many of the monthly values showed statistically significant increases, but the average increase for the period was less than 0.2 mg L^{-1}. Block cutting caused Na^+ concentrations to increase by a maximum of 0.2 to 0.3 mg L^{-1}, but the increases did not last beyond the second year after harvest.

Ammonium. Ammonium in streams from an undisturbed forest seldom exceeds 0.1 mg L^{-1} and usually is less than 0.02 mg L^{-1}. Strip cutting and block clearcutting had no detectable effect on NH_4^+ in stream water.

Hydrogen. Results are illustrated by a plot of weighted, monthly means of H^+ expressed as both mg L^{-1} and pH (Fig. 7). Streams from the three study watersheds had small but consistent differences in H^+ during the preharvest period. These differences of 0.002 to 0.020 mg L^{-1}, spanning a pH of 4.7 to 5.7, are typical of natural variation between watersheds at Hubbard Brook (Johnson 1979).

Strip cutting caused H^+ in streamflow to be more variable and slightly elevated in the second and third years of harvest (Fig. 7). During these 2 years, H^+ averaged 0.005 ± 0.003 mg L^{-1}, representing an average increase in H^+ of 0.002 to 0.003 mg L^{-1}, or a decrease in pH from 5.7 to 5.3.

For the block clearcutting, increases in H^+ appeared in the first spring after harvest, and elevated levels of 0.010 to 0.025 mg L^{-1} occurred through the second summer after harvest (Fig. 7). On the basis of the pretreatment relationship with the control watershed, these values represent an average increase of about 0.004 mg L^{-1}, or a decline in pH from 5.0 before harvest to 4.8 for the first 2 years after harvest. After the second summer, H^+ in stream water declined gradually to 0.002 to 0.004 mg L^{-1} (pH 5.4 to 5.7), or below the average of 0.010 mg L^{-1} (pH 5.0) that occurred for the watershed during preharvest.

Nitrate. During the calibration period, streams from the study watersheds showed cyclic NO_3^- concentrations related to seasonal growth patterns of vegetation. Minimum concentrations of 0.05 mg L^{-1} occurred in summer and autumn. The concentration rose in late autumn as vegetation became dormant, reaching maxima of up to 5 mg L^{-1} in March or April, then decreasing to low levels in May and June (Fig. 8).

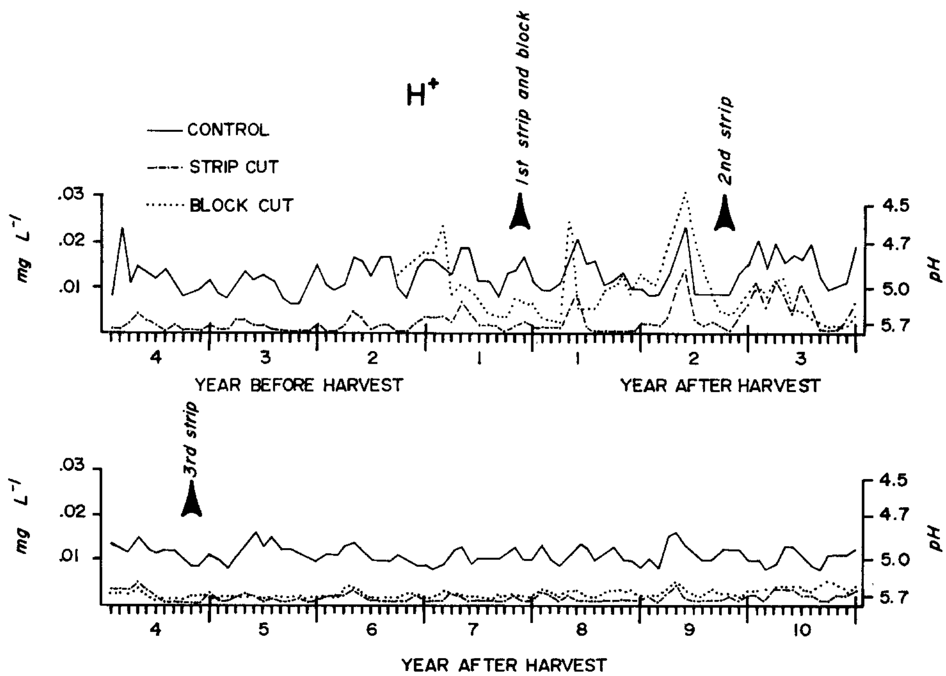

Figure 7.—Weighted, mean monthly H^+ and pH in stream water, by calendar year.

Nitrate increased immediately after strip cutting and remained higher than on the control watershed for 4 years. Average mean monthly concentrations were 2 mg L^{-1} higher than on the control for the first year after cutting, and 4 mg L^{-1} higher for the second year. After the second set of strips was cut, NO_3^- remained higher, but differences between watersheds were smaller. In year 6, NO_3^- for the strip cut dropped below the control and remained there through the 10th year (Fig. 8).

Nitrate did not respond to block cutting for 7 months, then rose over the next 11 months to a maximum of 26 mg L^{-1} (Fig. 8). This is an estimated increase of 23 mg L^{-1} compared with the control watershed. The NO_3^- concentrations then fell off rapidly and have been less than those on the control watershed since the middle of the third year after harvest.

Sulfate. Sulfate is the dominant anion in streams from the study watersheds. Seasonal patterns of SO_4 in streams from undisturbed forests usually show a gradual rise through the growing season to peaks of around 7 mg L^{-1} in late autumn and early winter, then a decline through the winter, reaching minimum concentrations of about 5.5 mg L^{-1} in late spring (Fig. 9).

Sulfate decreased after strip cutting. The decrease was most pronounced during late autumn and early winter of the first year after the first set of strips was cut. During this period, concentrations from the strip-cut watershed were about 1.5 mg L^{-1} below control watershed values (Fig. 9). Cutting the second and third sets of strips had less impact on SO_4^{2-}, and the control and strip-cut watersheds seldom differed by more than 0.5 mg L^{-1}.

The impact of block cutting on SO_4^{2-} is more difficult to discern. During the short time when determinations were made before cutting, SO_4^{2-} from the watershed to be block cut was below SO_4^{2-} from the forested control (Fig. 9). This difference continued after cutting, with maximum differences of more than 2 mg L^{-1} in the last half of the first and most of the second year after harvest. During the third and fourth years, SO_4^{2-} from the block cut began to approach values for the control, indicating that the differences in the 2 previous years were due to cutting.

Chloride. Chloride concentrations during preharvest averaged 0.5 mg L^{-1} for all study watersheds, and there were no seasonal patterns. In the summer after cutting of the first set of strips there was a mean increase of about 0.1 mg L^{-1}. The increase disappeared by winter and there

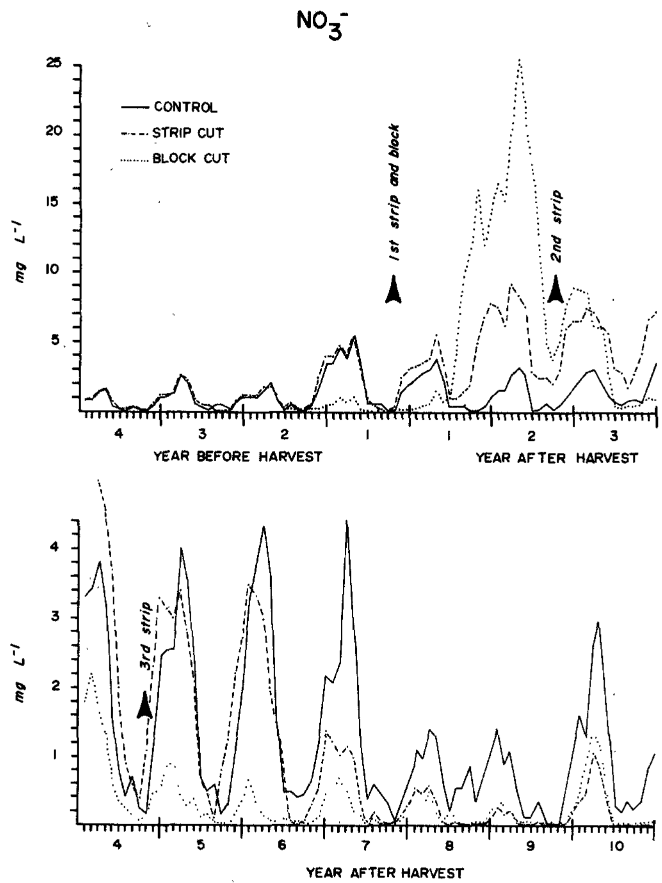

Figure 8.—Weighted, mean monthly NO_3^- in stream water, by calendar year. Note expansion of scale for years 4 through 10 after harvest.

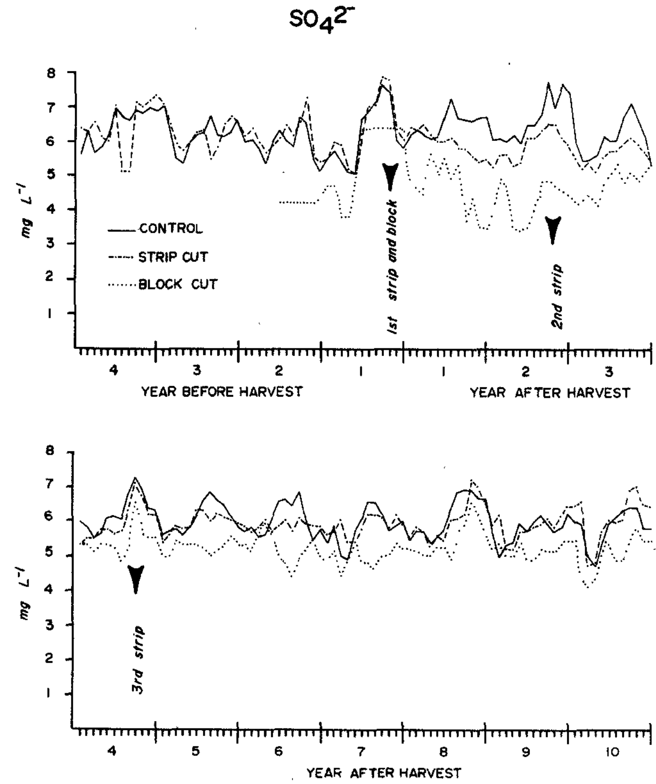

Figure 9.—Weighted, mean monthly SO_4^{2-} in stream water, by calendar year.

were no further changes due to strip cutting. Block cutting caused Cl^- to increase by a maximum of 0.4 mg L^{-1} in the first summer after harvest. This increase also was short lived and was absent by the second summer after harvest.

Cation-anion summary. A comparison of the ionic strength of stream water is a convenient way of summarizing effects due to harvest. Table 3 shows mean annual ion concentrations for year 1 before harvest and for year 2 and year 5 of the harvest period. For year 2 after harvest, when harvest effects were at a maximum, the sum of measured ions for the strip-cut and block-cut watersheds was 16 and 104 percent greater, respectively, than in year 1 before harvest. The same comparison for the control watershed shows a decrease of 7 percent in measured ions. By year 5 of the harvest period, the sum of measured ions had returned to levels found before harvest.

In terms of ion balance, SO_4^{2-}, the dominant anion showed a slight decline in year 2 after both strip and block cutting. However, large increases in NO_3^- resulted in net increases in the sum of anions. The increases in anions were countered by large increases in Ca^{2+} and Mg^{2+} on the strip cut and Ca^{2+}, Mg^{2+}, and K^+ on the block cut. Potassium is the only ion continuing to show an increase at year 5 of the harvest period.

Nutrient Budgets

Changes in stream volume and ion concentrations after strip and block cutting caused streamflow outputs of nutrients to differ from values for uncut forests. For the stream water ions that showed relatively small changes in concentration after harvest, such as Mg^{2+}, Na^+, NH_4^+, and Cl^-, the outputs increased in direct proportion to increases in stream volume. To illustrate, over the 10-year period considered in this paper, streamflows were increased by 4 percent by strip cutting and by 7 percent by block cutting (Table 1). Outputs for the nutrient ions listed previously were increased by about these same percentages. For

Table 3.—Cation-anion relationships in stream water of the study watersheds (values are weighted, annual means)

Item	Ca^{2+}	Mg^{2+}	K^+	Na^+	NH_4^+	H^+	Total cations	SO_4^{2-}	NO_3^-	Cl^-	Total anions	All ions
							ueq L^{-1}					
Strip cut												
Year 1 before harvest	100	35	6	53	2	3	208	133	39	16	188	396
Year 2 after harvest	127	40	8	54	1	5	235	121	87	16	224	459
Year 5 after harvest	94	31	11	49	1	1	187	123	31	12	166	353
Block cut												
Year 1 before harvest	64	34	5	39	1	11	154	115	6	14	135	289
Year 2 after harvest	139	55	21	42	0	14	271	90	211	17	318	589
Year 5 after harvest	71	26	13	33	1	2	146	110	5	11	126	272
Control												
Year 1 before harvest	77	32	6	41	2	14	172	129	34	16	179	351
Year 2 after harvest	69	28	5	37	1	15	155	135	22	15	172	327
Year 5 after harvest	67	27	5	34	1	12	146	127	37	14	178	324

nutrient ions that showed greater changes in concentration, such as Ca^{2+}, K^+, NO_3^-, and SO_4^{2-}, changes in outputs were more variable.

Calcium. The Ca^{2+} budget shows a sizeable net loss under forested conditions (Table 4). The input in precipitation for the 10 postharvest years was 11.5 kg ha^{-1}, while output in streamflow from the watersheds if they had not been cut was estimated as 165.5 kg ha^{-1}. Strip cutting further increased the output by an estimated 26.6 kg ha^{-1}, or 16 percent, while block cutting increased the output by 47.6 kg ha^{-1}, or 29 percent. More than two-thirds of the increase occurred in the first 3 years after initiation of strip cutting, and in the first 2 years after block cutting.

Potassium. The K^+ budget for uncut watersheds also shows a net loss (Table 4). Over the 10 years of study, outputs of K^+ in stream water were increased by 29.6 kg ha^{-1}, or 135 percent, as a result of strip cutting, and 48.0 kg ha^{-1}, or 218 percent, as a result of block cutting. The percentage increases are about 8 times greater than for Ca^{2+}. The changes in outputs were at a maximum in the first few years after harvest, but increases have been consistent throughout the postharvest period.

Nitrate. Nitrate values have been converted to NO_3-N for the input-output budget summaries. This allows direct comparison of N losses in later discussions about N capital of the study sites. Comparison of inputs in precipitation with outputs if the watersheds had not been cut shows a slight accumulation of NO_3-N (Table 4). Input over the 10-year study period was 52.9 kg ha^{-1}, and estimated output in the absence of cutting was 45.2 kg ha^{-1}. The substantial variability in annual outputs from undisturbed forests is thought to be related in part to the presence or absence of soil freezing (Likens et al. 1977).

As a result of strip cutting, outputs for the 10 years after harvest were increased by 22.3 kg ha^{-1}, or about 50 percent. Block cutting caused NO_3-N outputs to be increased by 57.8 kg ha^{-1}, or 128 percent. The largest increases occurred in years 1 through 3 after the start of the strip-cutting sequence, and in years 1 and 2 after block cutting. In years 6 through 10 after strip cutting, and 5 through 10 after block cutting, the harvested watersheds lost smaller amounts of NO_3-N in streamflow than if they had not been cut.

Sulfate. The SO_4-S budget shows a net loss on an annual basis (Table 4). The input in precipitation for the 10-year study period was 114 kg ha^{-1} as opposed to an output in streamflow of 185.9 kg ha^{-1} for the forested control watershed. Harvest resulted in relatively small changes, increasing SO_4-S output by 4.8 kg ha^{-1} after strip cutting, and decreasing SO_4-S output by 14.0 kg ha^{-1} after block cutting. The small changes indicate that the declines in concentration of SO_4^{2-} ions in streams were mostly compensated for by the increased volume of streamflow.

Table 4.—Annual input-output budgets for Ca^{2+}, K^{+}, NO_3-N, and SO_4-S, in kg ha^{-1}

Water year after harvest	Input in precipitation	Output if uncut	Changes in outputs due to: Strip cut	Block cut[a]
		Ca^{2+}		
1	1.2	14.9	+7.5*	+21.5
2	1.2	20.2	+6.1*	+11.5
3	2.0	28.3	+7.0*	+2.6
4	1.1	15.8	+1.4*	+0.3
5	0.9	22.3	+0.8	+1.5
6	1.1	13.9	+0.2	+0.5
7	0.8	15.4	+0.8	+2.6
8	0.8	12.2	+1.0	+3.0
9	1.1	10.8	+0.9	+1.6
10	1.3	11.7	+0.9	+2.5
Total	11.5	165.5	+26.6	+47.6
		K^{+}		
1	0.3	1.9	+1.0*	+9.1
2	0.5	2.5	+2.0*	+6.4
3	0.8	3.0	+4.6*	+6.4
4	0.5	2.1	+1.9*	+2.6
5	0.4	2.4	+4.7*	+5.5
6	0.4	2.0	+3.7*	+4.1
7	0.4	1.9	+3.6*	+4.0
8	0.6	1.9	+2.4*	+3.1
9	0.9	2.2	+2.9*	+3.7
10	0.8	2.1	+2.8*	+3.1
Total	5.6	22.0	+29.6	48.0
		NO_3-N		
1	8.3	8.9	+10.8*	+39.5
2	5.9	4.6	+9.3*	+17.9
3	7.0	8.0	+9.0*	+2.1
4	4.1	4.8	+0.2	0
5	4.6	5.4	+0.4	−0.7
6	5.0	4.8	−2.8	−0.4
7	4.3	1.8	+1.1*	0
8	5.0	1.5	−1.3*	0
9	3.8	2.7	−2.0*	−0.4
10	4.9	2.7	−2.4*	−0.2
Total	52.9	45.2	+22.3	+57.8

Continued

Table 4.—Continued

Water year after harvest	Input in precipitation	Output if uncut	Changes in outputs due to: Strip cut	Block cut[a]
		SO_4-S		
1	10.7	16.1	−1.5*	−1.9
2	14.3	21.3	−0.9	−3.0
3	17.7	27.6	+1.4	−1.3
4	10.3	17.0	+0.8	−0.6
5	11.9	23.4	+2.7*	−0.7
6	10.5	16.3	+2.1*	−1.4
7	10.0	19.1	+0.6	−1.7
8	11.0	16.4	−0.4	−1.1
9	7.4	13.5	−0.1	−1.4
10	10.2	15.2	+0.1	−0.9
Total	114.0	185.9	+4.8	−14.0

* Significant at 0.05 level of probability.

[a] Changes not tested for statistical significant because stream volumes for block cut were estimated by simulation.

Biomass and Nutrients Removed by Harvest

The harvesting operation removed an average of 50 metric t ha^{-1} of biomass from the strip-cut watershed and 65 metric t ha^{-1} from the block clearcut (Table 5). Before cutting, the watersheds were estimated to support 133 and 150 metric t ha^{-1} of aboveground, living, woody biomass, respectively (Whittaker et al. 1974). The removals represent 38 percent of woody biomass from the strip cut watershed and 43 percent of woody biomass from the block cut. The removal efficiency from the strip cut probably is lower because some trees on upper elevation strips were either unmerchantable or were on slopes too steep to log. In such cases the trees were felled, but left in place.

For nutrient removals in harvested products, the rank was Ca $>$ N $>$ K $>$ S $>$ Mg $>$ P (Table 5). Total nutrient element contents of aboveground, woody biomass for Hubbard Brook forests have been estimated by Whittaker et al. (1979) and Likens et al. (1977). When compared with these values, Ca removed in harvest represented 28 percent and 30 percent of aboveground total in woody biomass on the strip-cut and block-clearcut watersheds, respectively. Corresponding values for other nutrients were 26 and 30 percent for K, 31 and 33 percent for Mg, 21 and 25 percent for N, 31 and 35 percent for S, and 18 and 19 percent for P (Table 5).

Regeneration

Natural regeneration has flourished after both block and strip cutting. The density and mix of species changed dynamically in the postharvest period (Table 6). Numbers of stems increased rapidly after harvest and peaked in year 2 at about 1 million stems ha^{-1}. The number of stems for year 2 after harvest reached a maximum on the third set of strips to be cut. This maximum count resulted mainly from increased numbers of herbaceous stems (Table 6), and probably reflects the abundance of seed sources in the previously cut strips.

In terms of ground cover, the vegetation at year 2 after block cutting and each of the strip cuttings formed a dense tangle, averaging about 1.5 m in height. The only areas not revegetated were those under dense slash, or those severely gouged and rutted during logging. Such areas were sampled as part of the regeneration survey and amounted to less than 3 percent of the total watershed area. Dominance in terms of numbers of stems (Table 6) and biomass (Fig. 10) was shared by herbaceous species, especially *Aster acuminatus*, *Dennstaedtia punctilobula*, and *Uvularia sessilifolia*; by species of *Rubus*; by advanced regeneration of *Acer*; and by stump sprouts of *Fagus grandifolia*.

Table 5.—Biomass and nutrient removal in harvested stems

Harvest	Biomass	Ca	K	Mg	N	S	P
	Oven-dry metric t ha^{-1}	*kg ha^{-1}*					
				STRIP CUT			
Preharvest[a]	133	383	155	36	351	42	34
Removed	50	107	40	11	74	13	6
% Removed	38	28	26	31	21	31	18
				BLOCK CUT			
Preharvest[a]	150	466	176	43	392	51	36
Removed	65	139	52	14	97	18	7
% Removed	43	30	30	33	25	35	19

[a] From Whittaker et al. (1974, 1979) and Likens et al. (1977).

Between years 2 and 10 the canopy closed and tree species gained dominance in both height and biomass (Fig. 10). Although the ratio between total numbers of trees, herbs, and shrubs showed no drastic changes, competition reduced total stems at year 10 to several hundred thousand ha^{-1} (Table 6). Also by year 10, some tree species had achieved sufficient diameter growth to move into the lower diameter classes (Table 7). The three most common northern hardwood species, *Betula alleghaniensis*, *Acer saccharum*, and *Fagus grandifolia*, became prominent in terms of total numbers of stems by year 10. *Prunus pensylvanica*, an exploitive species (Bormann and Likens 1979), occurred in moderate numbers on the strip cutting and in large numbers on the block cutting, and usually dominated in terms of biomass as a result of having far more stems in the larger diameter classes (Table 7).

Total biomass was between 34 and 53 metric t ha^{-1} at 10 years after the cuttings (Table 8). These values represent 25 to 40 percent of the aboveground biomass before harvest. As mentioned previously, most of the biomass at 10 years was dominated by tree species, especially *Prunus pensylvanica*. For example, on the block clearcutting, the 51 metric t ha^{-1} of biomass at year 10 (Table 8) consisted of 29 t ha^{-1} of *Prunus pensylvanica*, 11 t ha^{-1} of *Betula alleghaniensis*, 4 t ha^{-1} of *Fagus grandifolia*, and 2 t ha^{-1} of *Acer saccharum*. The biomass for *Prunus pensylvanica* actually was beginning to show a decline, having peaked at 31 t ha^{-1} at year 7 after harvest. This decline is in line with the usual growth pattern followed by *Prunus pensylvanica* (Bormann and Likens 1979).

Discussion

Changes in Water Yield

The most important effect of strip and block cuttings on water yield at Hubbard Brook included:

1. Increases in annual water yield, most of which occurred in the growing season months of June through September.

2. Changes in timing of spring flows due to a speedup in snowmelt on the harvested watersheds.

These are the same effects that occurred after an earlier experiment on Hubbard Brook Watershed 2, which was clearfelled and then treated with herbicides (Hornbeck et al. 1970). In that experiment, for a 3-year period in which vegetation was controlled with herbicides, annual increases in streamflow averaged 288 ± 54 mm. For the first water year after the block clearcutting, the simulated increase in water yield was a comparable 278 mm (Table 1). For the first year after strip cutting, with only one-third of the watershed harvested, the increase in water yield was 22 mm.

The increases in water yield from the strip-cut watershed were not as large as might have been anticipated. Hibbert (1967) and Douglass and Swank (1972) suggest that for the Eastern United States, increases in water yield for the first year after forest cutting are roughly proportional to percentage reduction in basal area. Thus, increases in water yield

Table 6.—Number of trees, shrub, and herbaceous stems at 2 and 10 years after individual harvests (elevation ranges are low, 440 to 550m; mid, 550 to 650m; and high, 650 to 750 m; block cut spanned elevations 470 to 600 m, or closest to mid-elevation range on strip cut)

Species	First strip						Second strip						Third strip						Block cut	
	Low		Mid		Upper		Low		Mid		Upper		Low		Mid		Upper		Mid	
	Year 2	Year 10	Year 2	Year 10	Year 2	Year 10	Year 2	Year 10	Year 2	Year 10	Year 2	Year 10	Year 2	Year 10	Year 2	Year 10	Year 2	Year 10	Year 2	Year 10
	Thousands of stems ha^{-1}																			
Tree[a]	593	132	521	99	221	89	253	54	282	49	155	40	428	74	310	49	198	67	661	231
Shrub[b]	165	53	32	92	93	220	111	16	130	27	76	55	204	11	216	20	117	67	51	33
Herbaceous[c]	340	282	733	226	535	622	501	129	463	90	338	228	832	195	1160	108	772	542	297	183
All species	1098	467	1286	417	849	931	865	199	875	166	569	323	1464	280	1686	177	1087	676	1009	447

[a] Major tree species include: *Abies balsamea*, *Acer pensylvanicum*, *A. rubrum*, *A. saccharum*, *A. spicatum*, *Betula alleghaniensis*, *B.papyrifera*, *Fagus grandifolia*, *Fraxinus americana*, *Picea rubens*, *Populus spp.*, and *Prunus pensylvanica*.

[b] Major shrub species include: *Rubus spp.*, *Sambucus canadensis*, and *Viburnum alnifolium*.

[c] Major herbaceous species include: *Aster acuminatus*, *Dennstaedtia punctilobula*, *Dryopteris spinulosa*, *Lycopodium lucidulum*, *Maianthemum canadense*, *Oxalis montana*, *Trillium spp.*, *Uvularia sessilifolia*, and *Viola spp.*

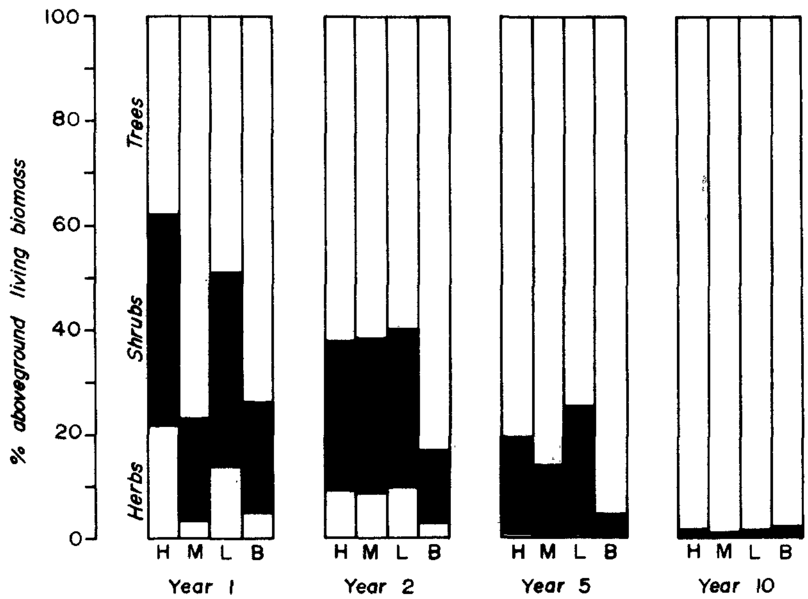

Figure 10.—Proportions of biomass occupied by trees, shrubs, and herbs on the second strip (H, M, and L are high-, medium-, and low-elevation zones) and the block clearcut (B).

after cutting the first set of strips may have been expected to be about 90 mm, or one-third of that occurring from that block cutting. The actual yield increase in year 1 from the strip cutting was less than one-tenth that from the block cut. And increases through the 10 postharvest years from the strip cuts were only 60 percent of those from the block cut (Table 1).

The explanation for the smaller than anticipated increases lies in the cutting configuration. A strip cut increases the crown exposure and transpiration rate of the residual trees that border the cut strips (Federer and Gee 1974). A portion of the added transpiration may be drawn from the extra water available in the cut strips, or from soil water moving downslope from cut into uncut strips. As a result, increases in streamflow are smaller than they would have been if the area had been cut in one large block. The larger increases for the first water year after cutting of the second and third sets of strips (Table 1) support this explanation.

Thus, it appears that strip cutting compared with block cutting is an inefficient form of forest harvest if augmentation of water yield is the most important consideration. The increases are small in relation to total area cut over. On the other hand, the smaller increases in water yield mean that there is less opportunity for nutrients to be transported from the watershed in dissolved and particulate forms.

Regarding the changes in timing of streamflow during snowmelt, the advances in snowmelt runoff that occurred after strip and block cutting were sizeable. However, when cutting is a small portion of a larger watershed, these advances quickly become unrecognizable when joining with streams from completely forested areas (Hornbeck and Pierce 1969). If the timing changes after cutting are to have a practical significance with regard to downstream flooding, thousands of hectares within individual, regional watersheds would have to be harvested. There seems little likelihood that clearcutting will ever be of sufficient scale in New England to bring about significant changes in downstream spring floods.

The rate at which water yield returns to preharvest levels should be strongly correlated with regrowth of vegetation. This is illustrated for the block clearcut by plotting annual increases in water yield in relation to increases in stand biomass (Fig. 11). Increases in water yield declined steadily with accumulating biomass, and were minimal when biomass reached 50 metric t ha^{-1}, or about one-third of the biomass found before harvest.

Erosion Losses in Streamflow

For undisturbed forests at Hubbard Brook, losses of nutrient elements via streamflow are greater in dissolved form than in sediment or particulate form (Bormann et al. 1969, 1974). The ratio for individual elements varies, but in terms

Table 7.—Stems ha^{-1}, by diameter class, for six major tree species occurring at year 10 after harvest

		First strip				Second strip				Third strip				Block clearcut			
		D.b.h. class				D.b.h. class				D.b.h. class				D.b.h. class			
Species	Elevation	<2.5	2.5-4.9	5.0-7.5	7.6-9.9	<2.5	2.5-4.9	5.0-7.5	7.6-9.9	<2.5	2.5-4.9	5.0-7.5	7.6-9.9	<2.5	2.5-4.9	5.0-7.5	7.6-9.9
		Stems ha^{-1}															
Betula alleghaniensis	Low	25,300	743	57	0	3,800	1,467	200	67	8,800	2,067	467	0				
	Mid	19,000	560	80	0	1,200	2,467	267	0	1,800	1,600	743	114	144,000	1,450	42	8
	Upper	23,500	629	171	57	5,000	3,257	229	0	13,700	2,333	267	0				
Acer saccharum	Low	36,800	57	0	0	27,500	2,533	333	67	37,500	1,200	67	0				
	Mid	45,500	240	80	0	24,600	1,533	267	0	25,000	1,829	229	0	16,800	341	17	0
	Upper	18,900	343	0	0	12,800	0	0	0	10,400	67	0	0				
Fagus grandifolia	Low	5,400	343	57	0	4,200	1,067	67	0	7,500	933	0	0				
	Mid	9,000	160	0	0	5,400	2,533	0	0	4,600	629	57	57	14,300	434	0	8
	Upper	7,600	571	0	0	2,500	914	171	57	9,600	1,200	67	0				
Prunus pensylvanica	Low	9,600	1,943	1,029	286	0	150	600	333	0	933	600	467				
	Mid	1,000	2,000	1,440	320	2,500	1,467	1,113	57	0	400	400	171	17,900	6,375	1,183	67
	Upper	1,800	857	171	171	2,800	1,029	514	57	1,700	200	133	0				
Acer pensylvanicum	Low	4,700	686	400	0	2,100	867	0	0	4,600	733	133	0				
	Mid	8,000	560	80	0	1,300	1,667	133	0	5,000	1,086	57	0	9,500	250	0	0
	Upper	5,000	0	0	0	5,400	229	57	0	10,000	133	0	0				
Acer spicatum	Low	5,000	229	0	0	2,100	2,067	267	0	0	133	0	0				
	Mid	0	0	0	0	0	400	0	0	3,200	229	0	0	300	8	0	0
	Upper	12,200	0	0	0	1,800	343	0	0	7,100	0	0	0				

Table 8.—Aboveground, living biomass at various years after strip cutting and block clearcutting

Year after harvest	First strip	Second strip	Third strip	Block clearcut
	Metric t ha^{-1}			
1	1	2	3	2
2	6	4	6	16
3	8	6	NA	24
4	12	10	9	NA
5	13	NA	NA	35
10	34	53	42	51

of gross export of mass, dissolved substances average about 165 kg ha^{-1} yr^{-1}, or about 5 times the amount lost in sediment or particulate form (Likens et al. 1977).

Our study did not determine sediment losses directly. However, the very small changes in the many turbidity readings obtained during and after harvests (Table 2) and in the material trapped in the weir basins indicate minimal changes in sediment or particulate losses resulting from harvest.

Of the two harvested watersheds, the block clearcut was thought to have the greater potential for erosion losses. Increases in water yield were greater after block clearcutting, increasing the chances for streambank and channel erosion, and no buffer strip was left. However, the turbidity data (Table 2) indicate that erosion losses after the block clearcut remained at the same low levels as from the strip cutting. The results confirm an earlier conclusion from the clearfelling and herbicide experiment on Hubbard Brook Watershed 2 (Bormann et al. 1974): northern hardwood ecosystems have an inherent resistance to erosion that can withstand cutting disturbances so long as the forest floor is not abused.

To protect the forest floor and maintain low erosion losses, known precautions were taken during logging. For example, logging was conducted in early autumn when chances for erosion and sedimentation are least. A buffer strip of trees was left along the stream channel in the strip cut, and efforts were made to avoid streamside zones in both the clearcut and strip cut. Skidroads were kept at lowest possible grades, and water bars were installed. These efforts, together with rapid revegetation, prevented serious erosion and resulted in minimal changes in nutrient losses in suspended or particulate form, and preservation of the high quality of forest streams at Hubbard Brook.

Concentrations of Stream Water Ions

The changes in concentration of various stream water ions during our study paralleled those reported for other studies in northern hardwood stands in New England. The increases in Ca^{2+}, K^{+}, Mg^{2+}, and NO_3^{-} and decreases in SO_4^{2-} occurred after clearfelling and herbicide applications on Hubbard Brook Watershed 2 (Likens et al. 1970); after clearcuttings in the White Mountains of New Hampshire (Pierce et al. 1972; Martin and Pierce 1980); after a variety of clearcuttings located in Maine, New Hampshire, and Vermont (Martin et al. 1984); and after a whole-tree harvest in New Hampshire (Hornbeck and Kropelin 1982). The causes of the changes in concentrations are reasonably well understood, though not completely quantified.

Mechanisms affecting concentrations. Several mechanisms may be responsible for the changes in ion concentrations after harvest.

1. Blocking of uptake. Uptake of available nutrients by living vegetation can be sizeable. For example, annual uptake of Ca^{2+} by Hubbard Brook forests is estimated at 62 kg ha^{-1} (Likens et al. 1977). Clearcutting temporarily blocks uptake while decomposition goes forward and increases the amount of available nutrients in the dissolved inorganic fraction of the soil solution. The greater amounts of soil water resulting from reduced interception and transpiration provide a means of transport to streams. Calcium

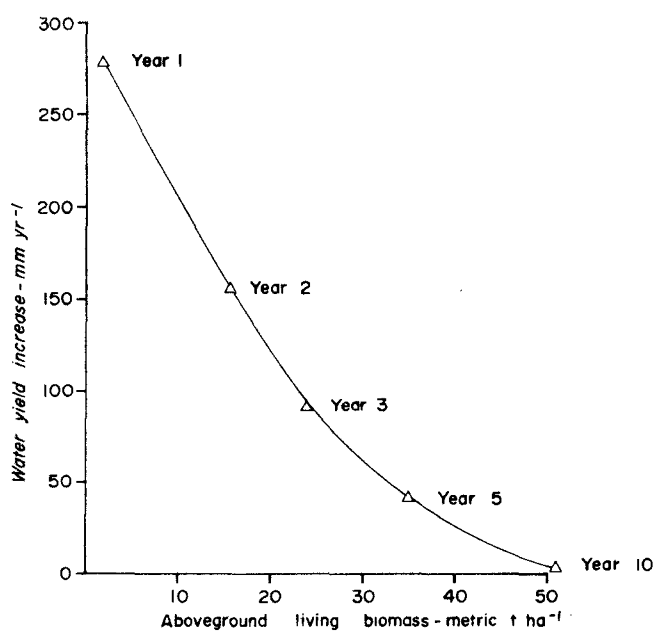

Figure 11.—Relationship of annual increases in water yield (the curve is hand-fitted).

probably is the best example of this mechanism, increasing to maximums in the first 1 to 2 years after harvest, then declining with regrowth (Fig. 5). Potassium shows this same pattern initially (Fig. 6), but does not fully decline with regrowth, indicating that other mechanisms are involved.

The decline with regrowth may involve other mechanisms. For example, in the Hubbard Brook Watershed 2 experiment in which the area was kept free of vegetation for 3 years, declines in concentrations began in the third year without revegetation. This suggests that exhaustion of easily decomposed substrate also plays a role in decreases in ion concentrations.

2. Critical element shunt. This mechanism is proposed by Bormann and Likens (1979) to operate as follows: in the first year after harvest, when C:N and element:P ratios of decaying organic matter are high, dissolved nutrients in soil solution are taken up by the increased numbers of microorganisms. As the C:N and element:P ratios decrease, and demands by microorganisms decline, nutrient ion export to streams increases. The critical element shunt may explain why nutrient ion concentrations are highest in the second year after harvest (Figs. 5, 6, 8, 9).

3. Accelerated nitrification. Nitrification rates in soils of undisturbed forests in New England are low, seldom exceeding 3 kg ha^{-1} mo^{-1} during the growing season (Federer 1983). However, the nitrification rate increases dramatically after cutting of northern hardwoods (Likens et al. 1970; Vitousek and Melillo 1979). The result is a flush of available NO_3^- and H^+, and, in turn, a mobilization of cations. The transport to streams is rapid, as indicated by the quick response of stream NO_3^- to cutting (Fig. 8). The fact that NO_3^- concentrations in streams fell below preharvesting levels in the fifth or sixth year of regrowth suggests several possibilities, including a corresponding decline in nitrification rates to levels below those in undisturbed forests, a greater uptake of N by the rapidly growing new stand, increased immobilization of N by soil organisms, or an increase in denitrification. These possibilities have not been tested for our study areas.

4. Accelerated decomposition of organic matter. Canopy removal exposes the forest floor and mineral soil to greater amounts of light, heat, and moisture, and accelerates decomposition and mineralization of organic materials (Bormann and Likens 1979). Covington (1981) showed that the forest floor in northern hardwood stands declines by about 50 percent in weight, or an average of 31 t ha^{-1} in the 15 years after clearcutting. One-third of this decline was estimated to occur in the first 3 years following cutting. During the 15-year degrading phase, it was estimated that net nutrient releases from mineralization of forest floor material were 35 kg Ca ha^{-1}, 31 kg Mg ha^{-1}, 44 kg K ha^{-1}, and 808 kg N ha^{-1}. These releases are a source for increased ion concentrations of soil water and streams.

5. Accelerated weathering of inorganic materials. Compared to decomposition of organic matter, weathering of mineral soil and rocks generally is a less active source of nutrients at Hubbard Brook (Likens et al. 1977). The increased exposure to heat and moisture that accelerates decomposition also should speed weathering rates, though this effect has not been quantified.

While these mechanisms occur after both strip and block cutting, increases in concentrations of stream ions due to strip cutting were less than one-third of those for block cutting. The small responses after strip cutting can be explained in part by mobile ions being intercepted and used by uncut or regenerating strips or the stream buffer zone. Also, the strip-cutting configuration should reduce decomposition and weathering by better protecting the cut sites from light and excessive heat. Thus, the availability of nutrients for leaching from the cut strips would be less than in the larger opening created by block clearcutting. Although the increases were smaller after strip cutting, the progression of three harvests caused them to last up to 2 to 3 times longer than increases after the block clearcutting.

Sulfate. A variety of hypotheses have been suggested for explaining the decrease in concentrations of SO_4^{2-} in streams after cutting. After the clearfelling of Hubbard Brook Watershed 2, Likens et al. (1970) attributed the decreases in SO_4^{2-} partly to dilution by the increased water yields and partly to the reduction of SO_4^{2-} generation by sources internal to the ecosystem. Fuller et al. (1986) suggested the same hypotheses for streams from a whole-tree harvest at Hubbard Brook and added the possibilities of decreased dry deposition and increased SO_4^{2-} adsorption by soils. Regarding this latter possibility, Nodvin (1983) proposed that excess acid production by elevated nitrification rates increases the net positive charge on soil surfaces, and enhances adsorption of SO_4^{2-} ions. The theory was tested in the laboratory and found applicable for the Hubbard Brook Watershed 2 experiment involving clearfelling and herbicides, and would seem equally applicable for the strip-cut and block-clearcut watersheds.

Hydrogen. Changes in H^+ are of special interest in relation to effects of acid precipitation. The forest canopy at Hubbard Brook at least temporarily reduces H^+ in precipitation from 0.08 mg L^{-1} above the canopy to 0.01 mg L^{-1} beneath (Eaton et al. 1973). Felling of the canopy during harvest allows acid precipitation to fall directly on soils and streams and possibly have more impact. Also, as mentioned earlier, the increased nitrification rates accompanying harvest are acidifying and could combine with acid precipitation to accelerate acidification of soils and streams. The amount of H generated by this mechanism is substantial. Based on output of NO_3-N in stream water, increased nitrification in the first year after harvest resulted in H production of 2.8 kg ha^{-1} on the block clearcut and

0.6 kg ha^{-1} on the strip cutting. These values can be compared with the average annual input of H^+ in precipitation of 1.0 kg ha^{-1} (Likens et al. 1977) and the annual total of 2.5 kg ha^{-1} generated by all H^+ sources within an undisturbed Hubbard Brook watershed (Driscoll and Likens 1982).

Thus, it is not surprising that there were small increases in stream water H^+ of 0.001 - 0.002 mg L^{-1} after strip cutting and 0.004 mg L^{-1} after block clearcutting (Fig. 7). The increases were short lived, and after year 2 of the block clearcut, the H^+ fell 0.008 mg L^{-1} below preharvest levels. Such changes are barely detectable and any impacts on stream chemistry and biota would be extremely difficult to quantify. Concerns should not be totally dismissed as changes in H^+ of soils and soil solution could be more pronounced and of greater significance than those occurring in streams (Federer and Hornbeck 1985).

Management implications. Changes in concentrations of nutrient ions in streamflow raise at least three concerns: (1) importance as a loss from site nutrient capital, (2) potential for harming water quality, and (3) adverse or beneficial effects on stream biota. A later section relates the importance of dissolved ions to nutrient capital. Regarding water quality, no measured ion concentrations exceeded standards or guidelines established for protecting water for domestic or recreational use. Nitrate came closest, reaching a maximum of 26 mg L^{-1} after block clearcutting versus the established standard of 45 mg L^{-1} for drinking water. Relationships of changing ion concentrations to stream biota have had only minimal study. Noel et al. (1986) and Likens et al. (1970) reported increases in stream periphyton and macroinvertebrates after clearcutting northern hardwoods, but they did not separate effects of stream chemistry from those of light and temperature. Where there is concern about stream biota or water quality, our study shows that changes in stream ions resulting from even-age management practices can be moderated substantially by using strip cutting rather than block clearcutting.

Evaluation of Nutrient Removals and Leaching Losses

Nutrient removals and leaching losses for the strip-cut and block-clearcut watersheds are summarized in Table 9. The table also shows nutrient pools, which serve as one basis for evaluating the importance of nutrient removals and losses. Such evaluations are not straightforward as there are still many unknowns. To illustrate, Figure 12 shows hypothetical curves of nutrient fluxes that would have to be quantified to fully evaluate harvest effects on site productivity. Such data would be needed for all nutrients likely to become growth limiting, and for stages of stand development beyond the critical 10-year regeneration period shown in Figure 12. While forest ecosystem studies at many locations are gradually providing these kinds of data and information, detailed evaluations of harvest impacts cannot yet be made.

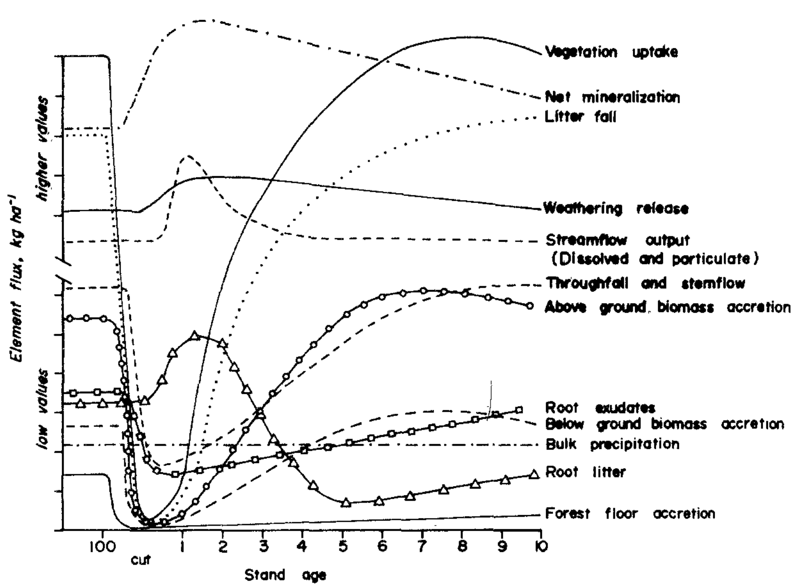

Figure 12.—Hypothetical curves of changes in fluxes of nutrient elements, such as Ca, K, and Mg, in years 1 through 10 after harvest.

Table 9.—Summary of nutrient removals, leaching losses, and nutrient pools

Item	Ca		K		Mg		N		S		P	
	Strip cut	Block clearcut	Strip cut	Block clearcut	Strip cut	Block clearcut	Strip cut	Block clearcut	Strip cut	Block clearcut	Strip cut	Block clearcut
	kg ha^{-1}											
Removal by harvest	107	139	40	52	11	14	74	97	13	18	6	7
10-year dissolved ion losses in streamflow attributed to harvest	27	48	30	48	3	7	22	58	5	−14	0[e]	0[e]
Total losses due to harvest	134	187	70	100	14	21	96	155	18	4	6	7
	Estimated Preharvest Nutrient Pools, *kg* ha^{-1}											
Vegetation	383[a]		155[a]		36[a]		351[a]		42[a]		35[e]	
Roots	101[a]		63[a]		13[a]		181[a]		17[a]		29[e]	
Forest floor	372[a]		66[a]		38[a]		1100[a]		124[a]		57[e]	
Mineral soil:												
Available	510[a]		75[c]		41		26[d]		NA		NA	
Total[f]	9600[a]		5084[c]		7659		3600[d]		560[a]		2524[e]	
Total	10,456		5368		7746		5232		743		2645	
	Control Watershed, *kg* ha^{-1} yr^{-1}											
Dissolved ion input precipitation	1.7[b]		0.8[b]		0.5[b]		6.5[b]		11.9[b]		.04[e]	
Dissolved ion output streamflow	12.5[b]		1.9[b]		2.9[b]		3.7[b]		17.2[b]		.02[e]	
Net	−10.8[b]		−1.1[b]		−2.4[b]		2.8[b]		−5.3[b]		.02[e]	
Weathering release	21.1[a]		7.1[a]		3.5[a]		0[d]		0.8[a]		1.5[e]	
Net mineralization	42.6[a]		20.1[a]		6.1[a]		69.6[d]		5.7[a]		10.6[e]	

[a] Likens et al. (1977) and Whittaker et al. (1979).
[b] Mean for 1963 through 1981.
[c] Hornbeck and Kropelin (1982).
[d] Bormann et el. (1977).
[e] Wood (1980) and Wood et al. (1984).
[f] Includes available soil elements.

In the interim, several studies have evaluated nutrient removals and leaching by comparing them with both plant-available and total nutrient capitals of the harvest site (Freedman et al. 1981; Weetman and Webber 1972; Weetman and Algar 1983; Johnson et al. 1982; Hornbeck and Kropelin 1982). At least two of these studies point out that a more realistic value for such comparisons, and one that might ultimately prove useful to forest managers, lies somewhere between available and total capitals (Freedman et al. 1981; Hornbeck and Kropelin 1982).

In the evaluations that follow we compare nutrient removals and leaching losses with both available and total nutrient capitals. We used an approach developed by Bormann and Likens (1979) that incorporates some of the more important nutrient fluxes from Figure 12. This approach can be used only for the first 4 years after harvest as data are not yet available for additional years. Even so, evaluations now are far more thorough than was possible at the height of the clearcutting controversy in the early 1970's.

Calcium. Before harvest, estimated total and available capitals for Ca were 10,456 and 510 kg ha^{-1} respectively (Table 9), the largest values for any of the nutrient elements studied. Losses of Ca of 134 kg ha^{-1} due to strip cutting and 187 kg ha^{-1} due to block clearcutting (Table 9) represent 1.3 and 1.8 percent of total site nutrient capital, and 26 and 37 percent of available capital. The nutrient losses obviously are more impressive as proportions of available capital than of total capital. The major concern would seem to be that the available pool does not become limiting to regrowth during present and future rotations.

Using the approach from Bormann and Likens (1979), we compared some of the major fluxes of available Ca in the years immediately following harvest. The sum of Ca^{2+} losses in stream water plus Ca stored in regrowing biomass ranged from 45 to 61 kg ha^{-1} yr^{-1} the first 4 years after block clearcutting (Fig. 13). Mineralization of Ca from the forest floor (Covington 1981) could supply as much as one-third of the Ca^{2+} needed to satisfy streamwater losses and storage in biomass. The remainder, or at least 25 to 40 kg ha^{-1} yr^{-1}, may have to be drawn from other sources, especially mineral soil. The available pool in the mineral soil is maintained by several processes including weathering, which supplied 21 kg Ca^{2+} ha^{-1} yr^{-1} before harvest (Table 9), and should supply even greater amounts immediately after harvest. Mineralization in the mineral soil also should supply increased amounts of available Ca^{2+} after harvest. As another source, logging slash contains more than 200 kg ha^{-1} of Ca^{2+}, some of which should mineralize quickly in the years after harvest. Thus, it seems that at least initially there should be no major decline in the available pool. There are mechanisms to adequately replace stream water losses and biomass storage.

Potassium. The preharvest pools for K were estimated at 5,368 kg ha^{-1} for total capital and 75 kg ha^{-1} for available (Table 9). The combined losses due to harvest of 70 kg ha^{-1} for strip cutting and 100 kg ha^{-1} for block clearcutting represent 1.3 and 1.9 percent of the total capital and 93 and 133 percent of available. Concerns about K losses in relation to the available pool may be even greater than for Ca.

In the 4 years immediately after block clearcutting, the sum of K^+ losses in stream water plus K stored in biomass showed a linear increase (Fig. 13). Since estimated mineralization of K from the forest floor is relatively constant immediately after harvest (Covington 1981), contributions of K from other sources become increasingly more important with time. Combined mineralization and weathering before harvest were estimated to contribute 27 kg K ha^{-1} yr^{-1} to the available pool. As with Ca, there would seem to be a continued, adequate pool of available K after harvest. However, in contrast to Ca, increased losses of K^+ in stream water have not subsided completely. Continued evaluation will be required as more data are obtained.

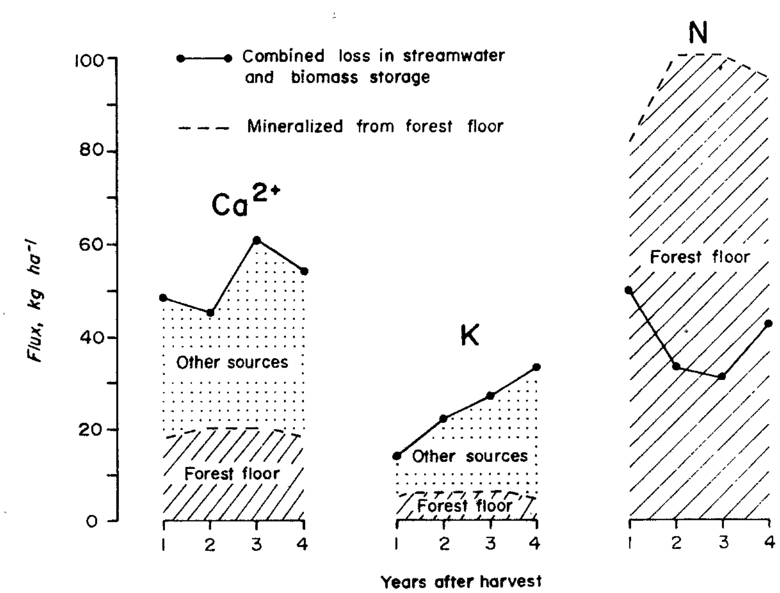

Figure 13.—Nutrient flux and sources in the initial 4 years after block clearcutting. Data on forest floor and biomass storage from Bormann and Likens (1979).

Magnesium. Magnesium pools before harvest were 7,746 kg ha^{-1} total and 41 kg ha^{-1} available (Table 9). Total losses due to strip cutting were 14 kg ha^{-1} or 0.2 percent of total and 34 percent of available. For block clearcutting, losses were 21 kg ha^{-1} or 0.3 percent of the total and 51 percent of available. The proportionally smaller losses for Mg compared with K reflect a tighter nutrient cycle for Mg. For undisturbed forests, combined weathering and mineralization for Mg is estimated at about 10 kg ha^{-1} yr^{-1} (Table 9). It seems unlikely that the Mg losses due to harvest would adversely affect regrowth. The losses of Mg are small and the reserve pool is large, and increased losses of Mg^{2+} in streamflow did not last beyond the second growing season after harvest.

Nitrogen. Nitrogen is of special interest because of concerns that it may be limiting to plant growth, even before harvest. Losses due to harvest of 96 kg ha^{-1} from the strip cut and 155 kg ha^{-1} from the block clearcut represent 1.8 and 3.0 percent of the estimated total capital of 5,232 kg ha^{-1} (Table 9). In terms of available capital of 26 kg ha^{-1}, the losses represent 369 percent for strip cutting and 596 percent for block clearcutting.

In contrast to Ca^{2+} and K^{+}, estimated mineralization of N from the forest floor after harvest is more than double the combined loss in stream water plus storage in biomass (Fig. 13). The fate of N lost from the forest floor is uncertain, but translocation to mineral soil and denitrification are possibilities (Bormann and Likens 1979). There have been large increases in NO_3^- in soil solution of mineral horizons after harvest of northern hardwoods (Hornbeck and Kropelin 1982), but it is not clear if the increases resulted from translocation out of upper horizons or from localized nitrification. The evaluation of denitrification has only recently been initiated at Hubbard Brook as part of a whole-tree harvesting experiment.

Increased nitrification and decomposition of the forest floor should provide adequate supplies of available N for regrowth immediately after harvest. However, there is some question as to whether available N is sustained through the regrowth period. To illustrate, Hornbeck and Kropelin (1982) found that NO_3^- in mineral soil solution increased 25-fold in the first 2 years after a whole-tree harvest of northern hardwoods. However, NO_3^- concentrations then declined rapidly, and by the fourth year after harvest were at levels below those in undisturbed forests. This pattern was similar in streamflow after harvest of our study watersheds at Hubbard Brook, indicating a potential for critical levels of available N by 4 to 5 years after harvest. Covington and Aber (1980) suggested that limited N at years 6 to 11 after clearcutting may be responsible for a decline in leaf production found in the exploitive species, *Prunus pensylvanica.* More research is needed on the N cycle to fully evaluate impacts on regrowth.

Losses of N resulting from harvesting may be replaced in part from atmospheric sources. The inputs of N in precipitation exceed outputs in streams by an average of about 3 kg ha^{-1} yr^{-1} (Table 9). Also, the only positively identified substrate for fixation of atmospheric N at Hubbard Brook is deadwood more than 2 cm in diameter (Roskoski 1980). Large amounts of this size material were left as slash on the harvested watershed. Roskoski (1980) estimated that about 2 kg N ha^{-1} yr^{-1} may be fixed in this material at year 4 after clearcutting.

Finally, there seems to be a mechanism for minimizing leaching losses of N after harvest. As shown in Figure 8 and Table 6, N losses in streamflow at 5 to 6 years after completion of harvest fell below those for undisturbed forests. Depending on how long this effect lasts, and assuming that N is not being lost in some other, unknown manner such as denitrification, N losses after harvest could be replaced by atmospheric sources in as little as 20 to 30 years. At the average net gain of 2.8 kg ha^{-1} for undisturbed forests (Table 9), the replacement time would be 34 to 55 years. This period could be even shorter if N fixation is found to be greater, a possibility suggested by the calculated mass balance of N for Hubbard Brook (Bormann et al. 1977).

Sulfur. Harvesting removed relatively small amounts of S and had little effect on S lost in stream water (Table 9). Sulfate-S occurs in high concentrations in streams (Fig. 9) and in soil solution (Hornbeck and Kropelin 1982) in our study area, both before and after harvest, and there is no apparent reason for concern about availability of S during regrowth.

Phosphorus. Removals of P in harvested products represented 0.2 percent of the preharvest P capital (Table 9). On the basis of research by Wood et al. (1984), we estimated that strip and block cutting did not increase losses of P in streamflow.

Total losses of P to harvest are small compared with the overall site capital. However, harvest may cause an important redistribution of soil P. Wood et al. (1984) point out that P is biologically conserved in the surface soil horizons of undisturbed forests at Hubbard Brook by the close coupling between decomposition and uptake. They suggest that harvest disrupts biological control of P and allows large amounts of P to move downward from the forest floor to B horizons. The time required to restore the P that moved from the forest floor is unknown.

Management implications. Overall, the nutrient losses resulting from strip cutting and block clearcutting at Hubbard Brook do not seem a major concern. Combined losses to increased leaching and product removal did not exceed 3 percent of total capital for any of the nutrients studied. In terms of available capital, the losses were more impressive, ranging from 26 to 596 percent. However, it appears that replacement mechanisms will be able to maintain the available pools at adequate levels. Nitrogen and K may be exceptions, particularly beyond the fifth year of regrowth. We are continuing to monitor K losses, and the nitrogen cycle is a central focus of a whole-tree harvest study in progress at Hubbard Brook.

Losses to harvest were less for strip cutting than for block clearcutting (Table 9)—partly because strip cutting moderated leaching losses, and partly because less material was harvested from the strip cut (Table 5). Management prescriptions for these watersheds call for harvesting again for sawtimber is not less than 70 years, and more likely in about 110 to 120 years (Leak et al. 1969; Solomon and Leak 1969). This should be adequate time to replenish the nutrients and organic matter lost as a result of harvest (Likens et al. 1978).

While the actual nutrient removals and increased leaching losses may not be a problem, transformations and redistribution of nutrients remaining on site could affect regrowth. As discussed, N may become limiting around year 5 of regrowth when nitrification declines to very low levels. The redistribution of P from organic to mineral soil also could affect regeneration. Strip cutting might moderate some of these effects, but more information is needed.

Regarding nutrient removals in harvested products, although our study watersheds were completely clearcut, the use of biomass was not intensive by current standards. The increasing use of newly designed, mechanized logging and processing equipment, and rising demands for wood as pulp and an energy source, have greatly increased biomass harvesting. Nutrient removals for whole-tree harvesting of northern hardwoods may be 2 to 3 times the values reported here (Hornbeck 1977; Hornbeck and Kropelin 1982). In such cases, and especially when coupled with projections for significantly shorter period betwen harvests, nutrient removals may be of much greater concern.

Regeneration

Regeneration on both the strip and block cuts is following the pattern outlined by Bormann and Likens (1979). Outgrowth, or occupation of the sites by exploitive and existing species, especially herbs and shrubs, peaked at about year 2 after harvest (Table 6). By year 10, upgrowth by tree species was well along and a closed canopy had formed. Dominant species at 10 years were *Prunus pensylvanica* and the three major northern hardwoods, *Betula alleghaniensis, Acer saccharum,* and *Fagus grandifolia. Prunus pensylvanica* usually dies at about 30 years, by which time the stands should be wholly dominated by northern hardwood species.

As mentioned at the outset, a prime objective of strip cutting is to regenerate high proportions of *Betula* and *Acer* in the new stand. It is difficult at this stage of regrowth to evaluate whether strip cutting has resulted in a more desirable species mix than block clearcutting. Little is known about what the species composition and stocking levels must be at age 10 to produce a commercially valuable northern hardwood stand. Strip cutting certainly appears successful in terms of total stems. *Betula alleghaniensis* and *Acer saccharum* were the most frequently occurring tree species on the strips at age 10 (Table 7).

Species composition differed markedly among the sets of strips (Table 10), partly because of environmental factors such as light, temperature, and moisture, and partly because of abundance of seed. Through year 10, stand development was optimum on the second and third strips, which had a favorable mix of species, especially in the 2.5–4.9, and 5.0–7.5 cm d.b.h. classes, and fewer *Prunus*

Table 10.—Species densities for trees more than 2.5 cm d.b.h. on harvested and control watersheds; observations for the strips and control stand are for the middle elevation range

Species	First strip (10 years)	Second strip (10 years)	Third strip (10 years)	Block clearcut (10 years)	Control[a] (60 years)
			stems ha^{-1}		
Betula alleghaniensis	640	2734	2457	1500	167
Acer saccharum	320	1800	2058	358	543
Fagus grandifolia	160	2533	743	442	387
Prunus pensylvanica	3760	2657	971	7625	11
Acer pensylvanicum	640	1800	1143	250	62

[a] Data for control stand from Bormann et al. 1970.

pensylvanica than on strip 1 or the block clearcut (Tables 7, 10). All strips had a more desirable mix of *Betula* and *Acer* compared with the undisturbed stand on the control watershed (Table 10). However, the current mix on the strips can be expected to undergo marked changes in the ensuing years. In other 15 years, regrowth on our study sites will be reaching an age for which more is known about species composition and stand development (Leak et al. 1969; Solomon and Leak 1969), and a more thorough evaluation of strip cutting will be possible.

Betula alleghanienis occurred in maximum numbers on the block clearcut, but *Prunus pensylvanica* was the second most numerous species (Table 7) and had by far the greatest biomass. Competition from *Prunus pensylvanica* may result in a lag in productivity of commercial species on the block clearcut compared with the strip cut. Regeneration strategies for *Prunus pensylvanica* are complex (Marks 1974; Marks and Bormann 1972), but the higher density of this species in the block cutting may be partly in response to a higher initial nutrient release after block cutting. Safford and Filip (1974) reported that fertilization greatly stimulated *Prunus pensylvanica* to the detriment of other commercial species in a 4-year-old northern hardwood stand.

The regrowth on both watersheds has other important roles, such as preventing erosion and curbing nutrient losses. The low turbidities in streams coupled with visual observations throughout the watersheds show that regrowth has stabilized all soil disturbance and that erosion will not be prolonged. Several Hubbard Brook studies have shown the important role reproduction plays in recovery of nutrient cycles immediately after harvest or other disturbances (Dominski 1971; Marks and Bormann 1972; Likens et al. 1978).

The density and rapidity of regrowth also are advantageous in helping to reduce the visual impacts of cutting. With regard to the visual or esthetic impact, strip cutting may be less displeasing than other forms of clearcutting. The uncut strips can be used to shield the cut areas from view, and break the openness created by large clearcut blocks and patches (Fig. 14).

Conclusion

Commercial clearcutting of northern hardwoods, whether by progressive strips or blocks, is a severe disturbance to the forest ecosystem. However, our study indicates that if care is taken during logging, and if sawtimber rotation lengths are followed, there should not be major adverse impacts on site nutrient capital, stand regeneration, or productivity. By the 10th year after harvest, hydrologic and nutrient budgets had returned nearly to preharvest levels, and a closed canopy had formed. Compared with block clearcutting, progressive strip cutting moderates effects on hydrologic and nutrient cycles, and may result in a more desirable mix of commercial species in the new stand.

Acknowledgment

Vincent Levasseur, forest technician at the Hubbard Brook Experimental Forest, maintained instruments and installations and collected much of the basic hydrologic and climatic data used in this paper.

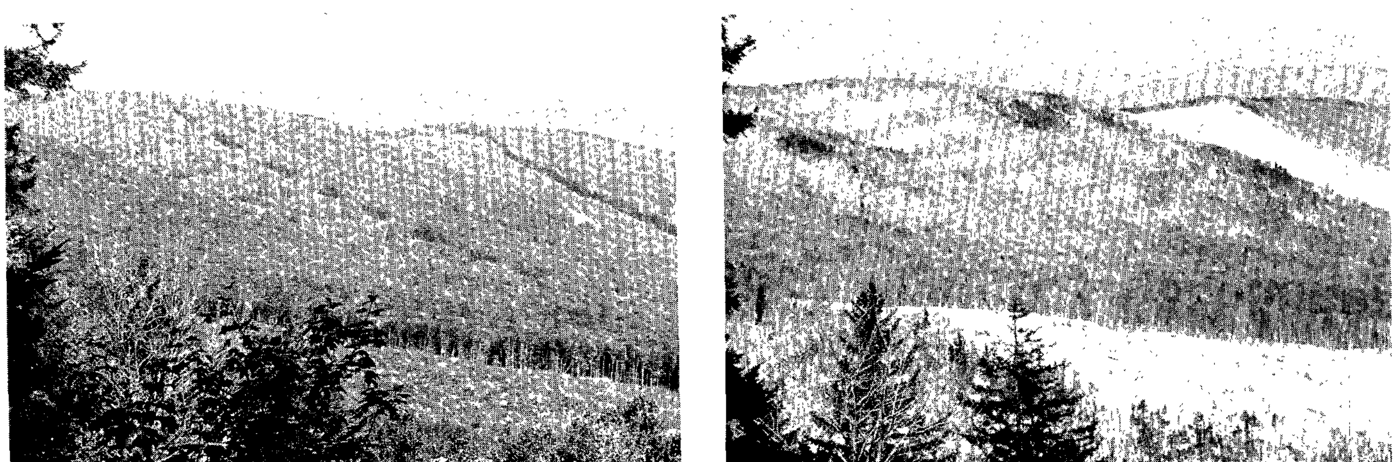

Figure 14.—Summer and winter views across block clearcut (foreground), strip cutting (center), and clearfelling (far right).

Literature Cited

Bormann, F. H.; Likens, G. E. **Pattern and process in a forested ecosystem**. New York: Springer-Verlag; 1979. 253 p.

Bormann, F. H.; Likens, G. E.; Melillo, J. M. **Nitrogen budget for an aggrading northern hardwood forest ecosystem**. Science. 196: 981–983; 1977.

Bormann, F. H.; Likens, G. E.; Siccama, T. G.; Pierce, R. S.; Eaton, J. S. **The effect of deforestation on ecosystem export and steady-state condition at Hubbard Brook**. Ecological Monographs. 44: 255–277; 1974.

Bormann, F. H.; Siccama, T. G.; Likens, G. E., Whittaker, R. H. **The Hubbard Brook Ecosystem Study: composition and dynamics of the tree stratum**. Ecological Monographs. 40: 373–388; 1970.

Bormann, F. H.; Likens, G. E.; Eaton, J. S. **Biotic regulation of particulate and solution losses from a forested ecosystem**. Bioscience. 19: 600–610; 1969.

Covington, W. W. **Changes in forest floor organic matter and nutrient content following clearcutting in northern hardwoods**. Ecology. 62: 41–48; 1981.

Covington, W. W.; Aber, J. D. **Leaf production during secondary succession in northern hardwoods**. Ecology. 61: 200–204; 1980.

Dominski, A. S. **Nitrogen transformations in a northern hardwood podzol on cutover and forested sites**. New Haven, CT: Yale University; 1971. 157 p. Ph.D. thesis.

Douglass, J. E.; Swank, W. T. **Streamflow modification through management of eastern forests**. Res. Pap. SE-94. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station; 1972. 15 p.

Driscoll, C. T.; Likens, G. E. **Hydrogen ion budget of an agrading forested ecosystem**. Tellus. 34: 283–292; 1982.

Eaton, J. S.; Likens, G. E.; Bormann, F. H. **Throughfall and stemflow chemistry in a northern hardwood forest**. Journal of Ecology. 61: 495–508; 1973.

Federer, C. A. **Nitrogen mineralization and nitrification: depth variation in four New England soils**. Soil Science Society of America Journal. 47: 1008–1014; 1983.

Federer, C. A.; Gee, G. W. **Tree water stress relation to water yield in a hardwood forest**. Res. Rep. No. 7. Durham, NH: University of New Hampshire, Water Resources Research Center; 1974. 30 p.

Federer, C. A.; Hornbeck, J. W. **The buffer capacity of forest soils in New England**. Water, Air, and Soil Pollution. 26: 163–173; 1985.

Federer, C. A.; Lash, D. **Brook: a hydrologic simulation model for eastern forests**. Res. Rep. No. 19. Durham, NH: University of New Hampshire, Water Resources Research Center; 1978a. 84 p.

Federer, C. A.; Lash, D. **Simulated streamflow response to possible differences in transpiration among species of hardwood trees**. Water Resources Research. 14: 1089–1097; 1978b.

Filip, S. M. **Natural regeneration of birch in New England**. In: Birch symposium proceedings; 1969 August 19–21; Durham, NH. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1969: 50–54.

Freedman, B.; Morash, R.; Hanson, A. J. **Biomass and nutrient removals by conventional and whole-tree cutting of a red spruce-balsam fir stand in central Nova Scotia**. Canadian Journal of Forest Research. 11: 249–257; 1981.

Fuller, R. D.; Driscoll, C. T.; Lawrence, G. B. **Sulfate transport in a northern forested ecosystem**. Program of the 4th international congress of ecology; 1986 August 10–16; Syracuse, NY; 1986: p. 154.

Hibbert, A. R. **Forest treatment effects on water yield**. In: International symposium on forest hydrology; 1965 August 29–September 10; University Park, PA. New York: Pergamon Press; 1967: 527–543.

Hornbeck, J. W. **Accuracy in streamflow measurements on the Fernow Experimental Forest**. Res. Note NE-29. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1965. 8 p.

Hornbeck, J. W. **Nutrients: a major consideration for intensive forest management**. In: Proceedings of symposium on intensive culture of northern forest types; 1976 July 20–22; Orono ME. Gen. Tech. Rep. NE-29. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1977: 241–250.

Hornbeck, J. W.; Kropelin, W. **Nutrient removal and leaching from a whole-tree harvest of northern hardwoods**. Journal of Environmental Quality. 11: 309-316; 1982.

Hornbeck, J. W.; Pierce, R. S. **Changes in snowmelt runoff after forest clearing on a New England watershed**. In: Proceedings of 1969 annual meeting, eastern snow conference. Eastern Snow Conference; 1969: 104–112.

Hornbeck, J. W.; Pierce, R. S.; Federer, C. A. **Streamflow changes after forest clearing in New England**. Water Resources Research. 6: 1124–1132; 1970.

Horwitz. E.C.J. **Clearcutting: a view from the top**. Washington, DC: Acropolis Books Ltd; 1974. 179 p.

Johnson, D. W.; West, D. C.; Todd, D. E.; Mann, L. K. **Effects of sawlog vs. whole-tree harvesting on the nitrogen, phosphorus, potassium, and calcium budgets of an upland mixed oak forest**. Soil Science Society of America Journal. 46: 1304–1309; 1982.

Johnson, N. M. **Acid rain: Neutralization within the Hubbard Brook ecosystem and regional implications**. Science. 204: 497–499; 1979.

Johnson, N. M.; Likens, G. E.; Bormann, F. H.; Fisher, D. W.; Pierce, R. S. **A working model for the variation in stream water chemistry at the Hubbard Brook Experimental Forest, New Hampshire**. Water Resources Research. 5: 1353–1363; 1969.

Leaf, C. F.; Alexander, R. R. **Simulating timber yields and hydrologic impacts resulting from timber harvests on subalpine watersheds**. Res. Pap. RM–133. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1975. 20 p.

Leak, W. B.; Solomon, D. S.; Filip, S. M. **A silvicultural guide for northern hardwoods in the Northeast**. Res. Pap. NE–143. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1969. 34 p.

Likens, G. E.; Bormann, F. H. **Chemical analyses of plant tissues from the Hubbard Brook Ecosystem in New Hampshire**. Bull. No. 79. New Haven, CT: Yale University School of Forestry; 1970. 25 p.

Likens, G. E.; Bormann, F. H.; Johnson, N. M.; Fisher, D. W.; Pierce, R. S. **Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem**. Ecological Monographs. 40: 23–47; 1970.

Likens, G. E.; Bormann, F. H.; Pierce, R. S.; Eaton, J. S.; Johnson, N. M. **Biogeochemistry of a forested ecosystem**. New York: Springer-Verlag; 1977. 146 p.

Likens, G. E.; Bormann, F. H.; Pierce, R. S. Reiners, W. A. **Recovery of a deforested ecosystem**. Science. 119: 492–496; 1978.

Marks, P. L. **The role of pin cherry (*Prunus pensylvanica*) in the maintenance of stability of a northern hardwood ecosystem**. Ecological Monographs. 44: 73–88; 1974.

Marks, P. L.; Bormann, F. H. **Revegetation following forest cuttings: Mechanisms for return to steady state nutrient cycling**. Science. 176: 914–915; 1972.

Marquis, D. A. **Germination and growth of paper birch and yellow birch in simulated strip cuttings**. Res. Pap. NE–54. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1966. 19 p.

Marquis, D. A. **Silvical requirements for natural birch regeneration**. In: Birch symposium proceedings; 1969 August 19–21; Durham, NH. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1969: 40–49.

Martin, C. W.; Noel, D. S.; Federer, C. A. **Effects of forest clearcutting in New England on stream chemistry**. Journal of Environmental Quality. 13: 204–210; 1984.

Martin, C. W.; Pierce, R. S. **Clearcutting patterns affect nitrate and calcium in New Hampshire streams**. Journal of Forestry. 78: 268–272; 1980.

Nodvin, S. C. **Effects of disturbance on decomposition processes and on sulfur cycling in the northern hardwood forest**. Ithaca, NY: Cornell University; 1983. 185 p. Ph.D. thesis.

Noel, D. S.; Martin, C. W.; Federer, C. A. **Effects of forest clearcutting in New England on stream macroinvertebrates and periphyton**. Environmental Management. 10: 661–670; 1986.

Patric, J. H. **Soil erosion in eastern forests**. Journal of Forestry. 78: 268–272; 1976.

Patric, J. H.; Evans, J. O.; Helvey, J. R. **Summary of sediment yield data from forested land in the United States**. Journal of Forestry. 82: 101–104; 1984.

Pierce, R. S.; Hornbeck, J. W.; Likens, G. E.; Bormann, F. H. **Effect of elimination of vegetation on stream water quality and quantity**. In: International symposium on results of research on representative and experimental basins; 1970 December 1–8; Wellington, NZ. Publ. No. 96. Washington, DC: International Association of Scientific Hydrology; 1970: 311–328.

Pierce, R. S.; Martin, C. W.; Reeves, C. C.; Likens, G. E.; Bormann, F. H. **Nutrient losses from clearcuttings in New Hampshire**. In: National symposium on watersheds in transition; 1972 June 19–22; Fort Collins, CO. Proc. Ser. No. 14. Minneapolis, MN: American Water Resources Association; 1972: 285–295.

Reinhart, K. G.; Pierce, R. S. **Stream-gaging stations for research on small watersheds**. Agric. Handb. 268. Washington, DC: U.S. Department of Agriculture; 1964. 37 p.

Roskoski, J. P. **Nitrogen fixation in hardwood forests of the northeastern United States**. Plant and Soil. 54: 33–44; 1980.

Safford, L. O. **Silvicultural guide for paper birch in the northeast (revised)**. Res. Pap. NE-535. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1983. 29 p.

Safford, L. O.; Filip, S. M. **Biomass and nutrient content of 4-year-old fertilized and unfertilized northern hardwood stands**. Canadian Journal of Forest Research. 4: 549–554; 1974.

Siccama, T. G.; Bormann, F. H.; Likens, G. E. **The Hubbard Brook Ecosystem Study: productivity, nutrients, and phytosociology of the herbaceous layer**. Ecological Monographs. 40: 389–402; 1970.

Singh, V. P., ed. **Applied modeling in catchment hydrology**. Littleton, CO: Water Resources Publications; 1982. 571 p.

Sollins, P.; Grier, C. C.; McCorison, F. M.; Cromack, K., Jr.; Fogel, R. **The internal element cycles of an old-growth Douglas-fir ecosystem in western Oregon**. Ecological Monographs. 50: 261–285; 1980.

Solomon, D. S.; Leak, W. B. **Stocking, growth, and yield of birch stands**. In: Birch symposium proceedings; 1969 August 19–21; Durham, NH. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northestern Forest Experiment Station; 1969: 106–118.

U.S. Department of Agriculture. **Silvicultural systems for the major forest types of the United States**. Agric. Handb. 445. Washington, DC: Department of Agriculture; 1973. 124 p.

Vitousek, P. M.; Melillo, J. M. **Nitrate losses from disturbed forests: patterns and mechanisms**. Forest Science. 25: 605–619; 1979.

Weetman, G. F.; Algar, D. **Low-site class black spruce and jack pine nutrient removals after full-tree and tree-length logging**. Canadian Journal of Forest Research. 13: 1030–1036; 1983.

Weetman, G. F.; Webber, B. **The influence of wood harvesting on the nutrient status of two spruce stands**. Canadian Journal of Forest Research. 2: 351–369; 1972.

Whittaker, R. H.; Bormann, F. H.; Likens, G. E.; Siccama, T. G. **The Hubbard Brook Ecosystem Study: forest biomass and production**. Ecological Monographs. 44: 233–254; 1974.

Whittaker, R. H.; Likens, G. E.; Bormann, F. H.; Eaton, J. S.; Siccama, T. G. **The Hubbard Brook Ecosystem Study: forest nutrient cycling and element behavior**. Ecology. 60: 203–220; 1979.

Wood, T. E. **Biological and chemical control of phosphorous cycling in a northern hardwood forest**. New Haven, CT: Yale University; 1980. 204 p. Ph.D. thesis.

Wood, T. E.; Bormann, F. H.; Voigt, G. K. **Phosphorous cycling in a northern hardwood forest: biological and chemical control**. Science. 223: 391–393; 1984.

Hornbeck, J. W.; Martin, C. W.; Pierce, R. S.; Bormann, F. H.; Likens, G. E.; Eaton, J. S. **The Northern hardwood forest ecosystem: ten years of recovery from clearcutting.** NE-RP-596. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1987 30 p.

Two even-age management systems, progressive strip cutting and block clearcutting, have been studied since 1970 on small watersheds at the Hubbard Brook Experimental Forest, New Hampshire. In the strip cutting, all merchantable trees were harvested in a series of three strips over 4 years (1970–74). In the block clearcutting, all trees were harvested in a single operation in 1970. This paper contrasts progressive strip cutting and block clearcutting for the 10-year period after initiation of harvest in terms of hydrologic response, erosion losses, stream water ions, nutrient leaching, nutrient removals in harvested products, and natural regeneraion of vegetation.

ODC 116.38

Keywords: water yield; watershed; hydrology; soil nutrients; nutrient cycling; nutrient budget; stand regeneration; Hubbard Brook

Headquarters of the Northeastern Forest Experiment Station are in Broomall, Pa. Field laboratories are maintained at:

- Amherst, Massachusetts, in cooperation with the University of Massachusetts.
- Berea, Kentucky, in cooperation with Berea College.
- Burlington, Vermont, in cooperation with the University of Vermont.
- Delaware, Ohio.
- Durham, New Hampshire, in cooperation with the University of New Hampshire.
- Hamden, Connecticut, in cooperation with Yale University.
- Morgantown, West Virginia, in cooperation with West Virginia University, Morgantown.
- Orono, Maine, in cooperation with the University of Maine, Orono.
- Parsons, West Virginia.
- Princeton, West Virginia.
- Syracuse, New York, in cooperation with the State University of New York College of Environmental Sciences and Forestry at Syracuse University, Syracuse.
- University Park, Pennsylvania, in cooperation with the Pennsylvania State University.
- Warren, Pennsylvania.

*U. S. GOVERNMENT PRINTING OFFICE: 1986-646-160:40014