

# LONG-TERM IMPLICATIONS OF FOREST HARVESTING ON NUTRIENT CYCLING IN CENTRAL HARDWOOD FORESTS

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**Abstract:** Fourteen years of streamflow and water quality data from the Leading Ridge Experimental Watersheds in central Pennsylvania were analyzed to determine the long-term impacts of a commercial forest harvest on stream water chemistry and nutrient loss. Clearcutting 44.5 ha of an 104-ha watershed resulted in significant increases in nitrate and potassium concentrations and significant decreases in calcium, magnesium, potassium, and sodium concentrations the first-year following harvesting. The lower concentrations resulted from a dilution effect caused by an increase in stream discharge. Although statistically significant, the observed changes in ionic concentrations did not cause any serious deterioration in stream quality. The changes in most solute concentrations, which were most pronounced during the growing season, appeared to return to pre-cutting levels by the third-year. However, concentrations of most macro-nutrients have periodically exceeded pre-harvesting levels as late as eleven years after harvesting. Although nutrient export increased, the losses were quite small, restricted to the first year, and did not appear to be sufficient to affect site fertility.

## INTRODUCTION

Changes in stream chemistry following timber harvesting were not considered a problem until the late 1960's following publication of results of a study on the Hubbard Brook Experimental Forest in New Hampshire (Bormann et al., 1968; Likens et al., 1970). Since then a number of studies have shown that changes in the concentration of a number of inorganic ions, all of which are important plant nutrients, do occur following timber harvesting (Aubertin and Patric, 1972; 1974; Corbett et al., 1978; Douglass and Swank, 1975; Federer et al., 1989; Hornbeck et al., 1987; Kochenderfer and Aubertin, 1974; Lynch and Corbett, 1990; Lynch et al., 1985; Lynch et al., 1975; Martin et al., 1984; Martin and Pierce, 1980; Reinhart, 1973; Swank and Douglass, 1975). Increases in nutrient concentrations following harvesting have been attributed to accelerated nutrient leaching due to exposure of the site to greater than normal amounts of heat, acceleration of the nitrification process, and increased leaching of nutrients due to the loss of uptake following plant removal (Likens et al., 1970). These studies have also shown that the changes are highly variable, very site

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specific, and generally related to the severity of the cut and the rate of revegetation of the cut-over area. The rate and degree of revegetation appear to control the longevity of increased nutrient concentrations.

Two things most forest harvesting-nutrient cycling studies have in common are that most have been restricted largely to nutrient concentrations and that most have been relatively short-term studies, lasting three to five years. Since timber harvesting, particularly clearcutting, substantially increases stream discharge (Hibbert, 1967; Lynch et al., 1972), evaluation of its impact on nutrient cycling must take this into consideration. For example, increases in nitrate concentrations that generally following forest harvesting are actually greater when dilution effects from increased flow are considered. Conversely, decreased concentrations of calcium and other ions, which are often observed and caused by a dilution effect attributed to increased flow, may actually represent an increase in export if the concentration-dilution effects are not linear. Consequently, the most effective way to evaluate the effects of forest management activities on nutrient cycling is to express the changes in both concentration (mg/L) and export units (kg/ha), the latter of which considers both concentration and discharge interactions.

The longevity of forest-management-nutrient-cycling studies are of particular interest since forest management activities can impact both the hydrologic regime and plant communities for tens of years. Consequently, the common practice of terminating a study three to five years after forest harvesting might be premature with regards to evaluating its total impact on nutrient cycling. Long-term changes in nutrient cycling can result from alteration of weathering processes, disruption of hydrologic flow paths, failure of water control devices, inadequate regeneration, and site disturbance due to unauthorized entry, among other things. Whenever any of these conditions prevail, the overall impact of forest harvesting on nutrient cycling and stream quality might persist for 10 to 20 years or more. Such long-term impacts have been assessed on the Hubbard Brook Experimental Forest in New Hampshire where impacts of forest harvesting on hydrologic and nutrient cycles were observed to last 10 years (Hornbeck et al., 1987). A study of long-term depletion of nutrients from six forests in eastern United States suggests that forest harvesting and increased leaching stimulated by atmospheric deposition could remove as much as 50% of the available calcium in only 120 years (Federer et al., 1989). However, the authors caution that additional research is needed because the uncertainties in the estimates are large.

The purpose of this paper is to report on short- and long-term changes in nutrient export from a 44.5-ha commercial clearcut in central Pennsylvania. The impacts of this commercial clearcut on nutrient concentrations, turbidity, sediment levels, and stream temperature, and the importance of these changes with respect to meeting Pennsylvania's water quality goals and EPA's anti-degradation policy of the Water Quality Act of 1987 were published earlier by Lynch and Corbett (1990).

## SITE DESCRIPTION

This study was carried out on the Leading Ridge Experimental Watershed Research Unit located in the Ridge and Valley Province of central Pennsylvania. This unit consists of three adjacent watersheds that are 123 (LR1), 104 (LR3), and 43 (LR2) ha in area. These watersheds were selected to be representative of approximately 4 million ha of forestland, much of which lies within established municipal watershed boundaries.

Watersheds within this research unit are equipped with modified broad-crested Trenton weirs with a sharp-crested, 90-degree, V- notch in the center to measure stream discharge. Streamflow is monitored using FW-1 water level recorders and a seven-day chart cycle. All watersheds have southeastern aspects and range in elevation from 244 to 442 m. Mean slopes on the watersheds vary from 12 to 17 percent, with maximum slopes approaching 50 percent. Most of the soils on the watersheds are residual, having developed in place through the weathering of underlying strata. Soils on the lower slopes are primarily silt loams and stony loams that are well drained and have high moisture holding capacity. The middle and upper slopes include well drained cobbly loams and stony loams with high moisture holding capacity. The ridge top is composed of cobbly and sandy loams. The average depth of the soil mantle is <2 m. Eight soil series are found on the watersheds. They include four Ultisols--Andover, Buchanan, Clymer, and Laidig--and four Inceptisols--Berks, Dekalb, Hazleton, and Weikert. Three major geologic formations underlie the watersheds. Most of the lower slope is underlain by Rose Hill shale. Castanea sandstone underlies the upper portion of the lower slope, middle slope, and most of the upper slope. Tuscarora quartzite underlies the ridge top.

Repeated timber harvesting plus the effects of fire and disease during the 1800's have resulted in the present-day, uneven-aged forest. Changes occur in the vegetative community from the valley to the ridge top. The ridge top and upper slope consists of a community of red oak (*Quercus rubra* Ashe.), chestnut oak (*Quercus prinus* L.), black oak (*Quercus velutina* Lamb.) and pitch pine (*Pinus rigida* Mill.). The lower slope and bottomland species include white pine (*Pinus strobus* L.), eastern hemlock (*Tsuga canadensis* (L.) Carr.), black birch (*Betula lenta* L.), red, black, and white oak (*Quercus alba* L.), and tulip poplar (*Liriodendron tulipifera* L.). The dominant understory include black gum (*Nyssa sylvatica* Marsh.), red maple (*Acer rubrum* L.), flowering dogwood (*Cornus florida* L.), and witch hazel (*Hammamelis virginiana* L.).

The climate of central Pennsylvania is of the humid, continental type. Although frontal storms are the most common source of precipitation, convectional showers are prevalent throughout the summer months. Monthly distribution of precipitation is such that approximately 25% more is received during the growing season (May-October) than during the dormant season (November-April). Monthly precipitation ranges from 11.66 cm in June to 5.92 cm in December. Annual precipitation averages approximately 112 cm.

The streams draining each basin develop from two perennial, first-order channels and several intermittent channels, all of which lie below the boundary of the upper slope unit. Runoff

takes place primarily as subsurface flow, rather than surface runoff. Monthly stream discharge, reported as a percentage of the total annual streamflow, increases steadily from October to April, after which it declines throughout the growing season. Historically, about 40% of the annual precipitation occurs as streamflow.

## RESEARCH APPROACH

The paired watershed method was used to evaluate changes in nutrient export and stream discharge following commercial harvesting on these central Pennsylvania watersheds. Leading Ridge Watershed One (LR1) was used as the undisturbed control watershed. Leading Ridge Watershed Three (LR3) was selected for the commercial clearcut. Changes in water quantity were based on linear regression analysis using 17 years of pre-harvest stream discharge measurements from both the treated and control watersheds. The annual and seasonal regression equations and measured stream discharge from the control watershed were used to predict stream discharge from the treated watershed assuming it had not been clearcut. The difference between the predicted discharge and the measured discharge on the harvested watershed represent the change in streamflow as a response to harvesting. Statistical significance of differences between predicted and measured values was determined using standard t-test techniques.

Changes in stream chemistry were based on chemical analyses of weekly stream water samples collected during a three-year calibration period (October, 1973 to September, 1976) and an 11-year post-harvest period. Statistical significance of differences between the control and harvested watersheds before and after harvesting were determined using analysis of variance techniques.

The entire timber sale was under the direction of the Pennsylvania Department of Environmental Resources, Bureau of Forestry, Rothrock District Forest. Harvesting, which was conducted following established Bureau policies, commenced on October 1, 1976 and ended on May 3, 1977; 44.5 ha of the 104-ha watershed were harvested. Rubber-tired tractor skidders were used to move the logs to the log landings. It was estimated that approximately 6% of the area cut was disturbed as a result of skidding activities. All logs were removed via an existing forest road that cut diagonally across the watershed from the ridge to the lower slope. The road was approximately 610 m in length.

In order to control nonpoint pollution during and following logging, the Best Management Practice (BMP) approach was used on this commercial harvesting. These BMP's included:

1. A protective buffer strip 100 feet wide was left on each side of all perennial streams. Logging of selective trees was permitted in the buffer zone.
2. The timber sale was divided into four blocks. Harvesting within a block had to be completed before cutting commenced in another block.

3. Skidding over perennial streams, except over approved culverts, was prohibited.
4. Slash was not permitted within 25 feet of any perennial or intermittent stream.
5. Logging activities were closely monitored by a forester from the Bureau of Forestry, especially during wet periods.
6. Main skid trails, logging roads, and log landings were carefully laid out by a forester from the Bureau.
7. Logging was prohibited during excessively wet periods.
8. Upon retirement, culverts were removed and water bars and other drainage devices installed on all logging roads and major skid trails. Logging roads were also graded to pre-logging conditions and gated.
9. Filtration strips between road surfaces and stream channels were utilized.
10. Road grades were limited to a maximum of 10 percent and a minimum of least 3 percent. Grades of 15 to 20 percent were permitted for short distances.
11. A performance bond was required prior to logging. This bond was set at 25% of the timber value.
12. Yearly inspections of the harvested area were conducted for five years.

Routine stream quality samples were collected weekly with some sampling during stormflow periods to assure that all discharge classes were represented. All samples were analyzed for pH, sulfate, calcium, magnesium, potassium, sodium, nitrate, and alkalinity ( $\text{CaCO}_3$ ) in the water quality lab of the Environmental Resources Research Institute at The Pennsylvania State University. All laboratory analyses followed methodology recommended by the Environmental Protection Agency (EPA, 1983).

Each water sample taken over the study period was matched with the hydrologic status of the stream as determined from the hydrograph. The hydrologic status and ionic concentrations were used to develop stream discharge/nutrient concentration relationships for each ion. These regression relationships were used to estimate ionic concentrations, which were then used in conjunction with the discharge data to estimate export of each ion from the watersheds. Daily export estimates were calculated for both watersheds and summarized by annual and seasonal periods. Statistical comparisons of pre- versus post-harvest concentration and stream discharge data using standard analysis of variance techniques were used to

evaluate the significance of the commercial harvest on nutrient export from this experimental watershed.

## RESULTS AND DISCUSSION

### Water Quantity

Water yield increases resulting from the commercial clearcut are given in Table 1. The first-year increase was 13.7 area-cm, all of which occurred during the growing season. The dormant season showed a non-significant decrease of 2.8 area-cm. The first-year increase is equivalent to 32 cm on an area-cut basis. The annual yield increase was sharply lower the second-year following harvesting amounting to only 3.4 cm. The second-year decrease was greater than generally reported for similar studies and was attributed to the rapid regrowth on the cut-over area that increased evapotranspirational losses and an unequal distribution of rainfall during the summer and early fall months. Rainfall was below normal for four of the six growing season months even though growing season precipitation was above normal. The magnitude of water yield increases is influenced strongly by the amount and distribution of both seasonal and annual precipitation (Lynch et al., 1972). The decreasing trend in water yield increases continued through the third growing season. By the fourth growing season, water yield increases were statistically unaffected by harvesting.

Table 1.--Annual and seasonal water yield increases following the commercial clearcutting of 44.5 ha on Leading Ridge Watershed Three.

| Water<br>Year<br>(May-April) | Water Yield Change             |                                |         |
|------------------------------|--------------------------------|--------------------------------|---------|
|                              | Growing<br>Season <sup>1</sup> | Dormant<br>Season <sup>2</sup> | Annual  |
| 1977                         | +14.55*                        | - 2.85                         | +13.72* |
| 1978                         | + 2.74*                        | + 0.43                         | + 3.43* |
| 1979                         | + 1.40*                        | - 1.04*                        | + 1.78* |
| 1980                         | + 0.13                         | + 6.04*                        | + 5.08* |
| 1981                         | - 3.31                         | - 1.12                         | - 3.66  |
| 1982                         | + 0.06                         | - 2.02                         | - 2.65  |
| 1983                         | + 0.79                         | + 0.13                         | + 1.44  |
| 1984                         | + 0.22                         | + 0.62                         | - 0.80  |
| 1985                         | + 0.30                         | + 0.72                         | + 2.23  |

\* Significant at 0.05 level

<sup>1</sup> May through October

<sup>2</sup> November through April

Stream chemistry concentration data for the clearcut and control watersheds prior to and following harvesting are presented in Table 2. Except for magnesium and sulfate, stream chemistry during the three-year calibration period was very similar on both watersheds. Following harvesting, the concentrations of most parameters underwent significant change. Calcium, alkalinity ( $\text{CaCO}_3$ ), magnesium, and sodium concentrations decreased the first-year as did specific conductance and pH; nitrate and potassium concentrations increased (Table 2). The reductions were attributed to dilution caused by an increase in stream discharge. Increases in nitrate and potassium concentrations were attributed to an increase in residue decomposition and a reduction in the uptake of these ions due to harvesting and a corresponding increase in leaching rates. The combined effects of dilution and increased nitrate leaching resulted in a decrease in pH the first year. As expected, changes in stream chemistry were most evident during the growing season.

A pattern similar to the first-year changes was observed the second-year after harvesting, although the magnitude of the changes were not as great. By the third-year, water yield increases were sharply reduced, thereby eliminating the effects of dilution on mean annual ionic concentrations (Table 2). Nitrate and magnesium concentrations were the only ions that were significantly elevated above pre-harvesting concentrations, although the increases were quite small. Essentially, stream chemistry on the clearcut watershed appeared to return to pre-cutting levels by the end of the third-year. However, this apparent return to pre-cutting levels was short-lived as a general increase in the concentrations of most parameters was observed the fifth year (Table 2). Associated with the increased concentrations of most of the macro-nutrients was an increase in alkalinity, pH, and specific conductance. Such increases were also noted the seventh and ninth years following harvesting but not in the tenth and eleventh years; nor were all parameters significantly elevated during the sixth and eighth years. This year to year variability in mean annual concentrations appeared to be related to differences in the amount and distribution of precipitation, particularly during the growing seasons, and its subsequent impact on ionic concentrations when compared to observed values during the three-year calibration period. Differences in climatic patterns and subsequent solute concentrations between pre- and post-harvesting periods makes it difficult to assign statistical significance to observed differences in stream quality. It should be noted that the three-year calibration period on this watershed is relatively long when compared to similar studies, but of insufficient length to permit the development of seasonal and annual predictive equations.

Significant increases in the concentrations of macro-nutrients and subsequent increases in alkalinity, pH, and specific conductance during the fifth and following years may have resulted from an increase in the weathering of parent materials on the watershed. This is supported by the fact that fluctuations in calcium, magnesium, and sodium were very similar and that each is a by-product of weathering. Temporal trends in stream water potassium, nitrate, and calcium concentrations for the control and harvested watersheds for both the calibration and post-harvesting periods are shown in Figures 1, 2, and 3.





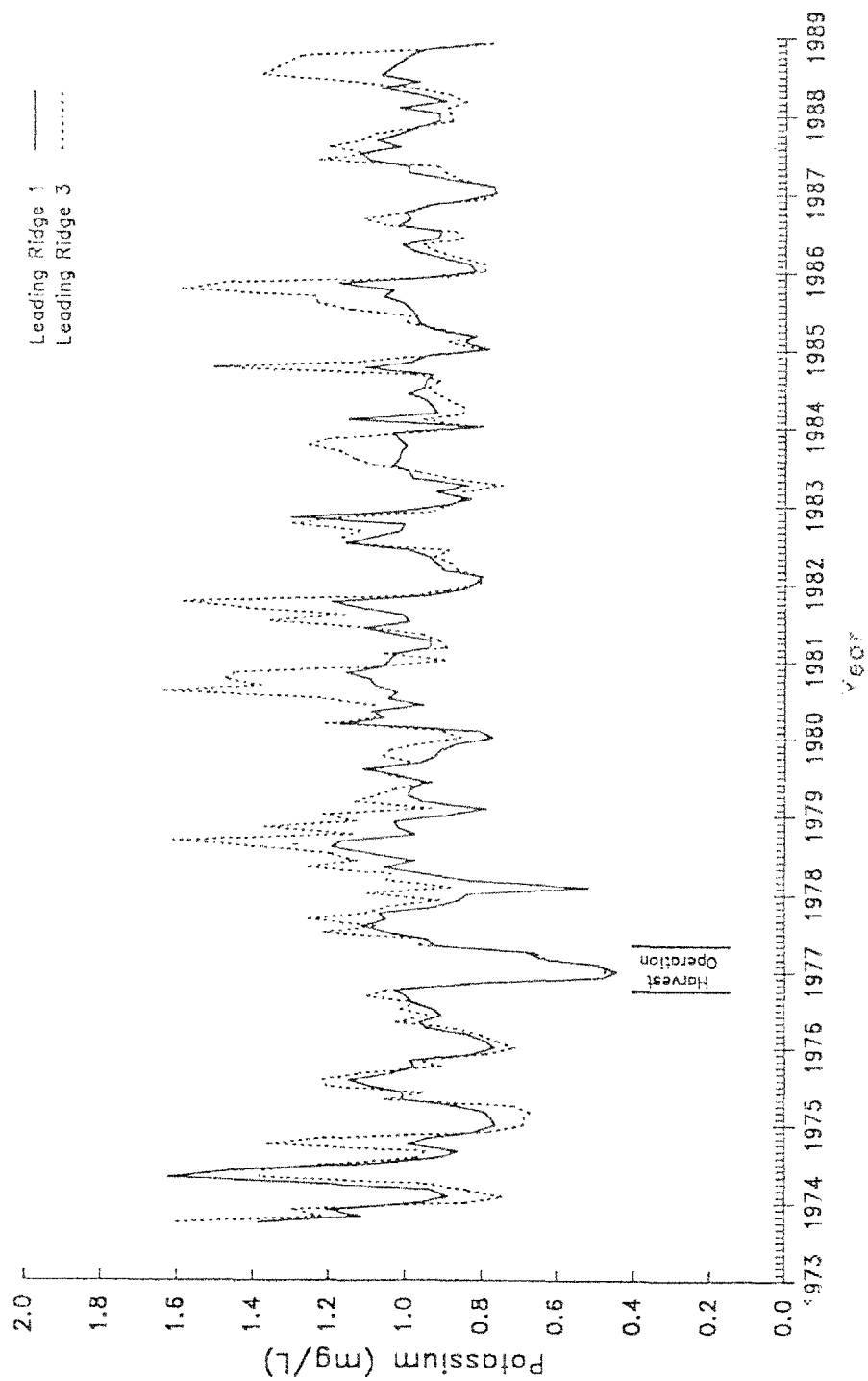


Figure 1. Trends in stream water potassium concentrations for the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977) and after harvesting.

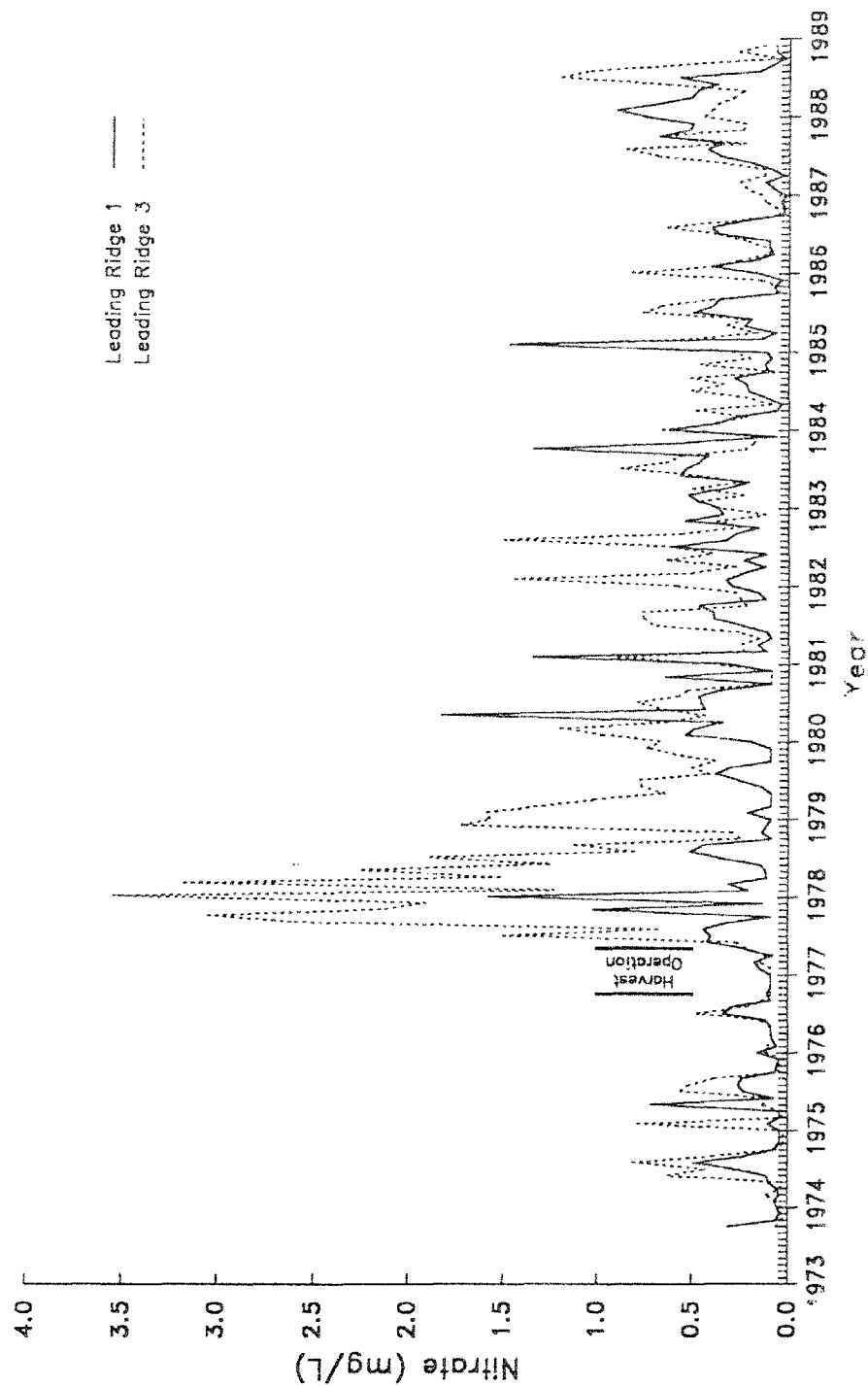


Figure 2. Trends in stream water nitrate concentrations for the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977) and after harvesting.

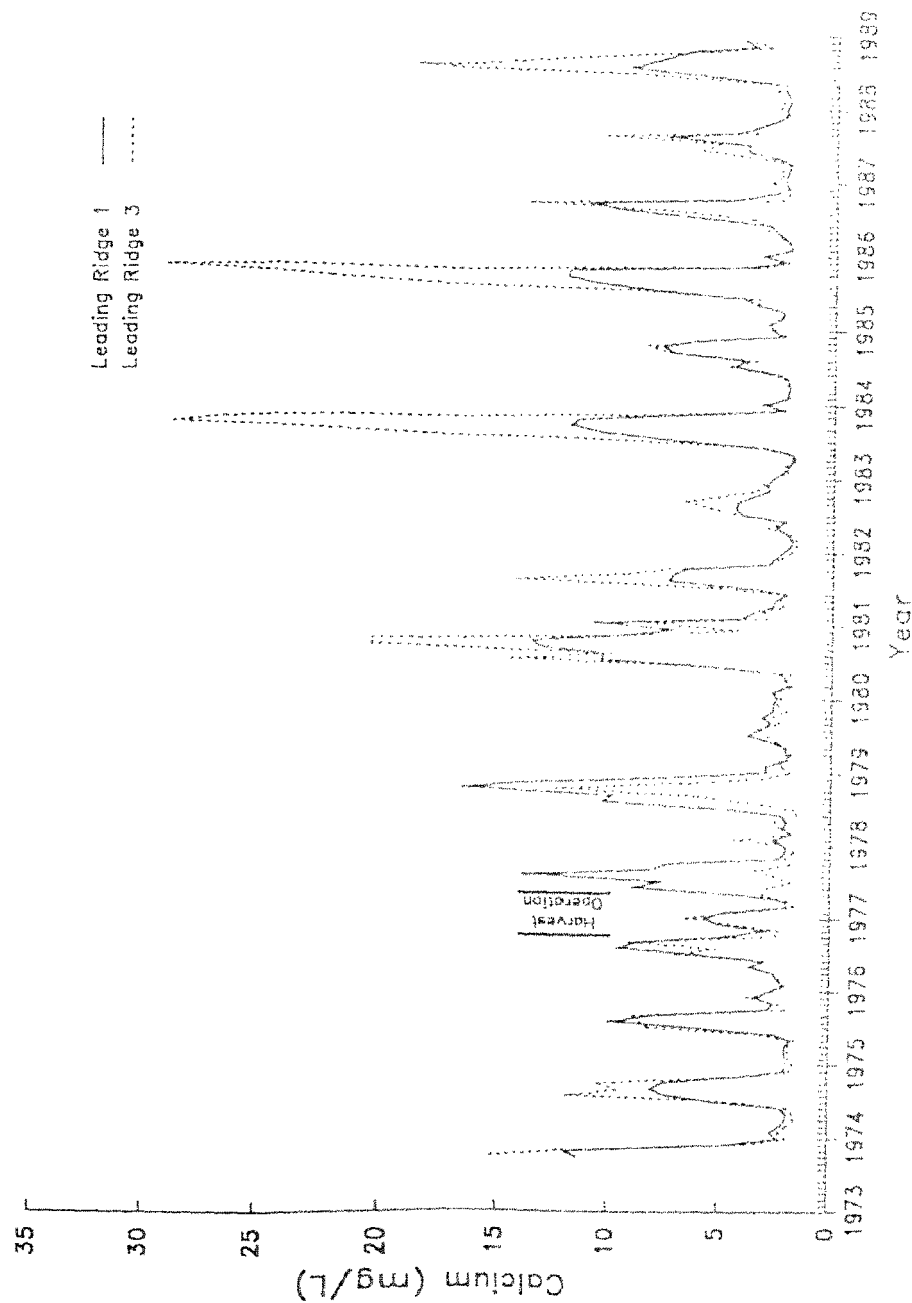


Figure 3. Trends in stream water calcium concentrations for the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977), and after harvesting.

## Nutrient Export

Clearcutting did increase the export of most nutrients from the watershed; however, the increases were restricted almost entirely to the first-year growing season (Tables 3 and 4). Calcium export increased from 12.1 kg/ha during the calibration period to 16.1 kg/ha the first-year after harvesting, but was only slightly higher the second-year. Almost all of the increased calcium export occurred during the growing season (Table 4) and was largely due to increases in stream discharge (Table 1) that were greatest the first-year growing season and decreased rapidly thereafter. Calcium export relationships between the clearcut and control watersheds during the remaining nine post-harvest years were essentially the same as those observed during the calibration period (Table 3, Figure 4) despite the fact that calcium concentrations were significantly higher during some of the latter post-harvest years (Table 2, Figure 3). Increased calcium concentrations during the fifth, seventh, and ninth years occurred during the growing season under low-flow conditions and thus accounted for only a small percentage of the total annual export. Over the 14-year study period, growing season calcium export accounted for an average of 30% of the annual calcium export on the control watershed and 32% on the clearcut watershed (Tables 3 and 4).

Magnesium and sodium export also increased the first-year (Table 3) with most of the increase occurring during the growing season (Table 4). Since magnesium and sodium concentrations actually decreased the first-year, the increased export resulted from an increase in stream discharge. Like calcium, magnesium and sodium export values returned to pre-harvesting levels by the second-year and have remained unchanged during the last nine years of the post-harvest period despite significant increases in sodium and magnesium concentrations during the seventh and ninth years following harvesting. As was the case with calcium, these increased concentrations occurred during low flow periods and consequently contributed little to total annual export. Although an increase in growing season export might be expected, the increased concentrations have been restricted largely to a one or two-month period in the latter part of the growing season under generally the lowest flow conditions. Since the growing season export data presented in Table 4 represent a six-month summary period (May 1 through October 31), small increases in concentrations for one or two months, especially the drier months of August through October, would have little effect on the overall growing season export.

Clearcutting increased both potassium (Figure 1) and nitrate (Figure 2) concentrations the first-year after harvesting. These increases, along with the increased stream discharge, resulted in a significant increase in potassium and nitrate export (Table 3), the bulk of which occurred during the growing season (Table 4). Like the other nutrients, potassium and nitrate export returned to pre-cutting levels by the second-year and have remained near pre-harvesting levels throughout the remainder of the post-harvest period (Figures 5 and 6). Again, slight increases in potassium and nitrate concentrations, primarily during the growing seasons, have been insufficient to significantly increase annual or seasonal export of these ions.

Table 3. Annual export (kg/ha) of important plant nutrients from the commercial clearcut (LR3) and control (LR1) watersheds before and following harvesting.

| Parameter | Pre-Harvest <sup>1</sup> |      | First Year |       | Second Year |      | Third Year |      | Fifth Year |      | Seventh Year |      | Ninth Year |      | Eleventh Year |      |
|-----------|--------------------------|------|------------|-------|-------------|------|------------|------|------------|------|--------------|------|------------|------|---------------|------|
|           | LR1                      | LR3  | LR1        | LR3   | LR1         | LR3  | LR1        | LR3  | LR1        | LR3  | LR1          | LR3  | LR1        | LR3  | LR1           | LR3  |
| Calcium   | 11.2                     | 12.1 | 12.1       | 16.1* | 11.0        | 12.5 | 14.5       | 15.9 | 7.8        | 8.5  | 10.9         | 11.9 | 9.3        | 10.6 | 9.7           | 9.9  |
| Magnesium | 7.3                      | 6.3  | 8.1        | 8.5*  | 7.3         | 6.3  | 9.8        | 8.4  | 4.8        | 4.1  | 7.1          | 6.0  | 6.0        | 5.3  | 6.2           | 5.1  |
| Potassium | 5.0                      | 5.1  | 5.7        | 7.2*  | 5.2         | 5.4  | 6.9        | 7.1  | 3.1        | 3.3  | 4.9          | 5.0  | 4.0        | 4.4  | 4.0           | 4.0  |
| Sodium    | 3.3                      | 3.7  | 3.5        | 5.0*  | 3.2         | 3.7  | 4.3        | 4.9  | 2.2        | 2.4  | 3.1          | 3.5  | 2.7        | 3.1  | 2.8           | 3.0  |
| Nitrate   | 0.18                     | 0.34 | 0.22       | 0.50* | 0.21        | 0.41 | 0.26       | 0.54 | 0.11       | 0.24 | 0.18         | 0.34 | 0.15       | 0.31 | 0.14          | 0.25 |

\* Significant at 0.5 level

<sup>1</sup> May 1 through April 30 water year

<sup>2</sup> Mean annual export for 1974 through 1976

Table 4. Growing season export (kg/ha) of important plant nutrients from the commercial clearcut (LR3) and control (LR1) watersheds before and following harvesting.

| Parameter | Pre-Harvest <sup>1</sup> |      | First Year |       | Second Year |      | Third Year |      | Fifth Year |      | Seventh Year |      | Ninth Year |      | Eleventh Year |      |
|-----------|--------------------------|------|------------|-------|-------------|------|------------|------|------------|------|--------------|------|------------|------|---------------|------|
|           | LR1                      | LR3  | LR1        | LR3   | LR1         | LR3  | LR1        | LR3  | LR1        | LR3  | LR1          | LR3  | LR1        | LR3  | LR1           | LR3  |
| Calcium   | 4.0                      | 4.5  | 2.8        | 5.8*  | 4.1         | 5.3* | 4.8        | 5.2  | 3.3        | 2.7  | 2.5          | 2.7  | 1.6        | 1.7  | 2.7           | 2.6  |
| Magnesium | 2.5                      | 2.2  | 1.7        | 3.0*  | 2.7         | 2.5  | 3.1        | 2.7  | 1.9        | 1.2  | 1.4          | 1.2  | 0.7        | 0.6  | 1.5           | 1.2  |
| Potassium | 1.7                      | 1.8  | 1.1        | 2.5*  | 1.9         | 2.2  | 2.0        | 2.2  | 1.2        | 0.9  | 0.9          | 0.9  | 0.3        | 0.3  | 0.9           | 0.9  |
| Sodium    | 1.1                      | 1.3  | 0.7        | 1.8*  | 1.1         | 1.5  | 1.4        | 1.6  | 0.9        | 0.7  | 0.6          | 0.7  | 0.3        | 0.3  | 0.7           | 0.7  |
| Nitrate   | 0.06                     | 0.12 | 0.04       | 0.17* | 0.08        | 0.19 | 0.07       | 0.15 | 0.04       | 0.05 | 0.03         | 0.06 | 0.01       | 0.02 | 0.03          | 0.04 |

\* Significant at 0.5 level

<sup>1</sup> May 1 through October 31

<sup>2</sup> Mean annual export for 1974 through 1976

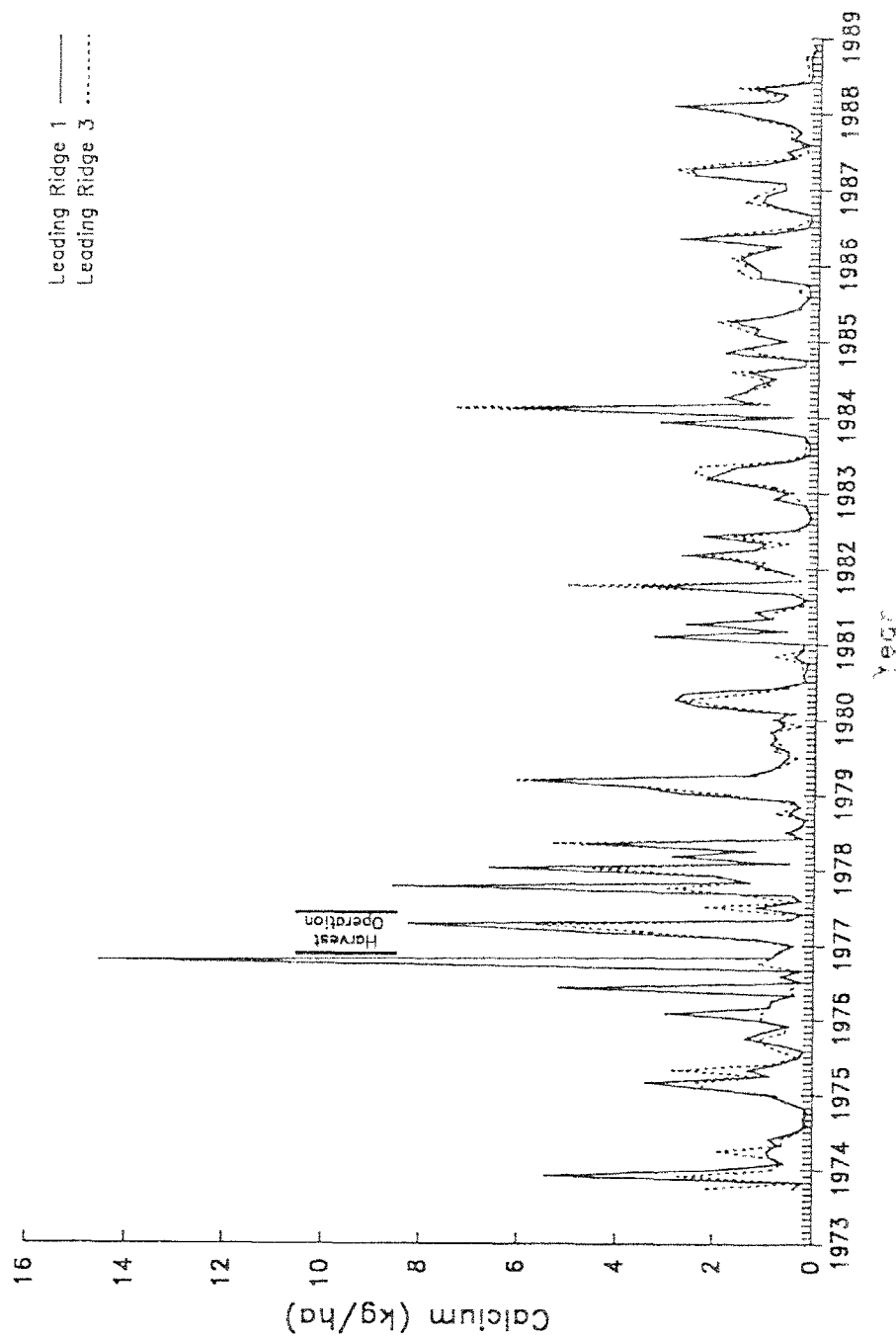


Figure 4. Trends in calcium export from the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977), and after harvesting.

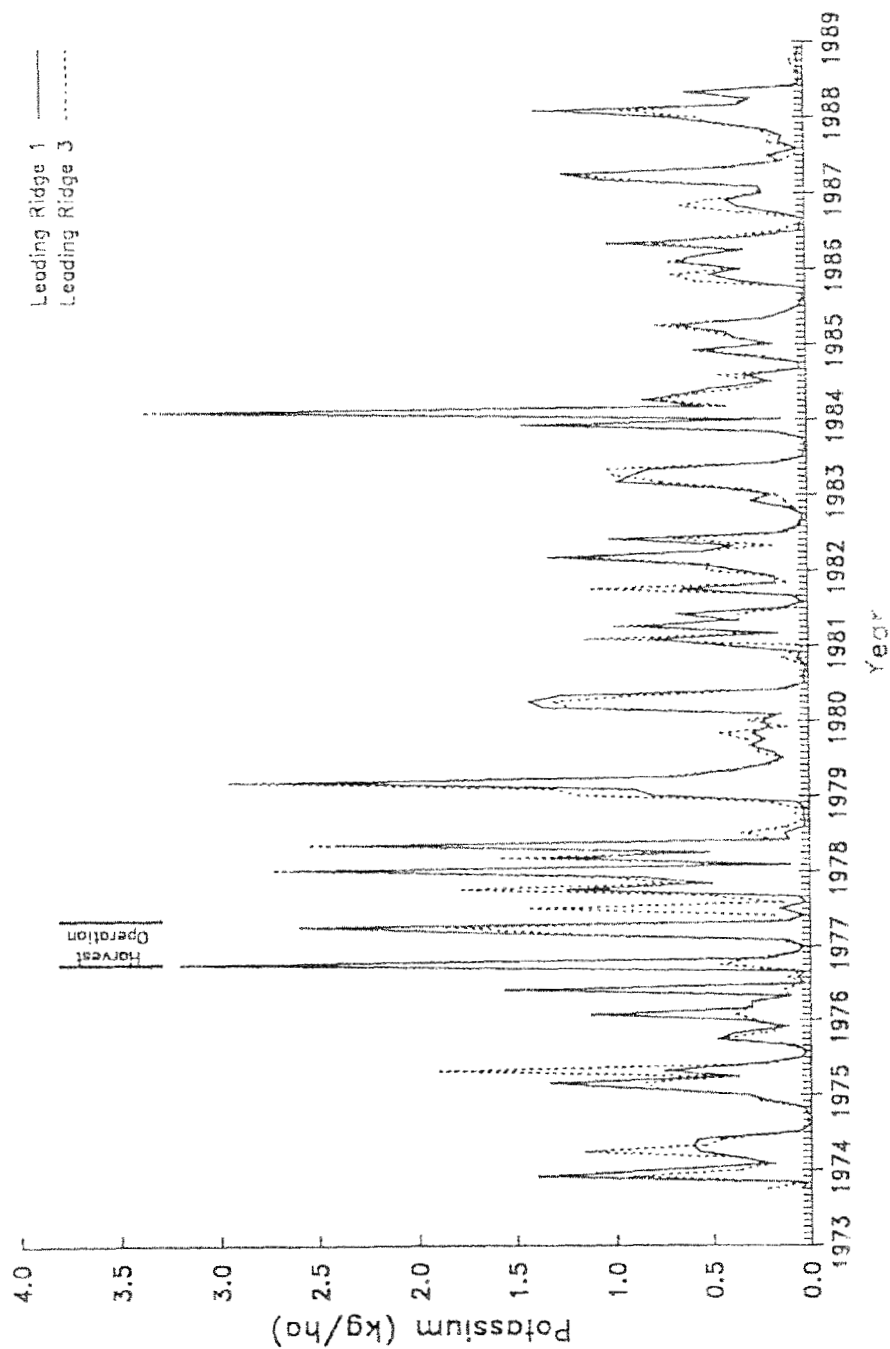


Figure 5. Trends in potassium export from the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977), and after harvesting.

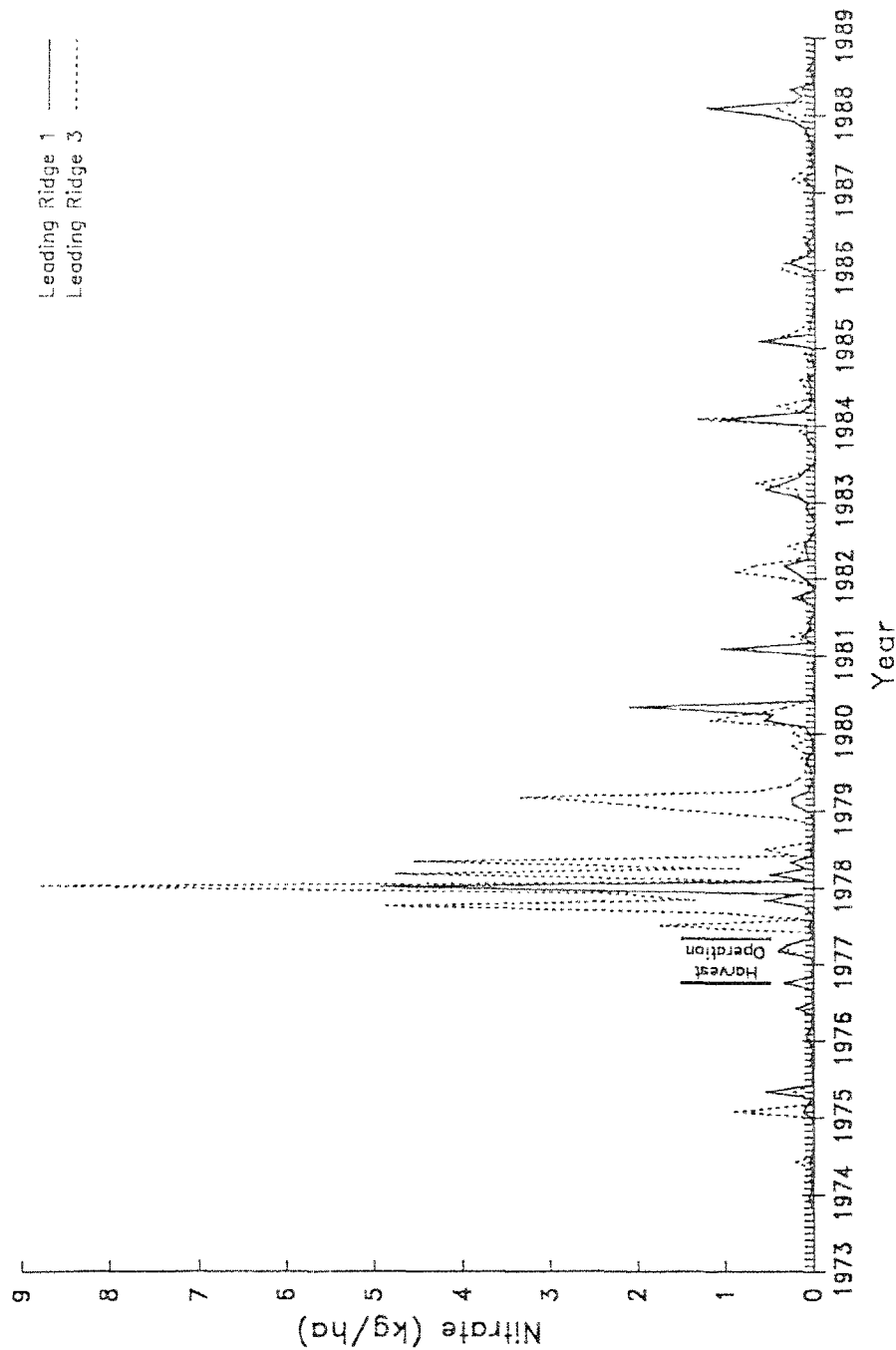


Figure 6. Trends in nitrate export from the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977), and after harvesting.



## SUMMARY

The observed changes in stream water chemistry do not represent a significant degradation of stream quality nor do they indicate a significant deterioration of site quality and fertility. Rapid recovery to pre-harvest levels and subsequent minimal nutrient loss was due largely to rapid revegetation of the cut-over area. Increases in nitrate concentrations were quite small and well below drinking water standards. Nevertheless, such small increases may violate EPA's anti-degradation policy of the Water Quality Act of 1987. This policy requires that surface water quality that exceed minimum state water quality standards be maintained at their existing water quality levels. EPA has been most stringent in applying this policy where pristine waters, such as those draining forested watersheds, are involved. Overall, it appears that the "Best Management Practices" developed by the Pennsylvania Bureau of Forestry were very effective in controlling nutrient loss from this silvicultural operation.

The results of this study clearly indicate the need for long-term forest management/nutrient export studies. Although not a component of this project, accurate estimates of total nutrient pools and nutrient losses through harvest removal under various forest harvesting practices should be a part of such studies in order to determine the significance of increased leaching with respect to long-term site fertility. Excessive leaching of calcium and other plant nutrients following harvesting have been suggested as a possible limiting factor in growth in intensively managed northeastern forests (Federer et al., 1989). However, the authors acknowledge that the uncertainties in their estimates are large and that further research is needed.

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