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8th Central Hardwood Forest Conference

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March 4-6, 1991

For attending this conference, each registrant was eligible for 12 hours of Continuing Forestry Education (CFE) credit offered by the Society of American Foresters.

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8TH CENTRAL HARDWOOD FOREST CONFERENCE

Proceedings of a Meeting

Held at

The Pennsylvania State University

University Park, PA

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Edited by

Larry H. McCormick and Kurt W. Gottschalk

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FOREWORD

This conference is the eighth in a series of biennial meetings that began in 1976 at Southern Illinois University. Other conferences have been hosted by Purdue University, University of Missouri, University of Kentucky, University of Illinois, and University of Tennessee. The purpose of these conferences has remained the same: to provide a forum for the exchange of information concerning the central hardwoods and to engender coordination among forest scientists in the central hardwood region. This purpose is evidently well-served: the last several conferences have each attracted some 45 to 65 program contributions, and the audiences have been correspondingly large.

Previous organizers have refrained from drawing precise boundaries around the "central hardwood region." We prefer to continue that policy on the grounds that to do otherwise might preclude some very worthwhile participation. Thus, while the principal focus has remained on the oak resource for reasons that are obvious, the ecological scope has broadened from oak-hickory (in the early meetings) to Appalachian oak (Knoxville and State College) and mesophytic forests. With a few exceptions, the commercially significant species are similar for all these forest types, and advancements in knowledge are of general interest.

But the central hardwood region is not merely a collection of similar forest types. It also has historical, demographic, political, and economic characteristics that tend to distinguish it from other forest regions of the United States. For example, the population is heavily rural and agricultural, primary wood markets tend to be diffuse and unorganized, wilderness values and endangered species have generally not been overriding issues, and a relatively minor proportion of the forest land is controlled by public agencies or corporate ownerships. These and related conditions play critical roles in the practice of forestry in this region, and in the aggregate they emphasize its distinction from other regions; but no single one is necessarily unique to the central hardwoods. For these reasons, the characteristics of nonindustrial private forest land owners in Massachusetts might be just as relevant to the central hardwood region as regeneration methods for white oak in Indiana.

Since these proceedings are being published in advance, we have no way of judging the ultimate success of the upcoming Eighth Conference. Of course, our earnest hope is that this meeting shall sustain the excellent reputation of the series. We believe this hope is encouraged by the quality of the papers in these proceedings.

REVIEW PROCEDURES

Each manuscript published in these proceedings was critically reviewed by at least two scientists with expertise in disciplines closely aligned to the subject of the manuscript. Reviews were returned to the senior author, who revised the manuscript appropriately and resubmitted it in a diskette format suitable for printing by the Northeastern Forest Experiment Station, USDA Forest Service where they were edited to a uniform format and type style. Manuscript authors are responsible for the accuracy and style of their papers.

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POSTER SESSION

RADIAL PATTERNS OF TREE-RING CHEMICAL ELEMENT CONCENTRATION IN TWO APPALACHIAN HARDWOOD STANDS

David R. DeWalle, Bryan R. Swistock, William E. Sharpe[1]

Abstract: Radial patterns in tree-ring chemical element concentration in red oak (*Quercus rubra* L.) and black cherry (*Prunus serotina* Ehrh.) were analyzed to infer past environmental changes at two mature Appalachian forest sites. Multiple cores extracted from five trees of each species at each site were divided into 5-yr segments, measured for length, composited, and analyzed for 19 elements using plasma emission spectroscopy. Radial patterns of tree-ring chemical elements were categorized into three types: elements showing relatively constant radial concentration in an inner wood zone with increased concentrations in an outer wood zone near the cambium, elements showing relatively constant radial concentration distributions with no rise near the cambium and elements showing gradually increasing concentrations from pith to cambium. Piece-wise multiple regression with correction for serial correlation was used to develop models of these patterns. Significant effects on chemical element concentrations by basal area growth rates and the outer 15 years of growth were detected. With the possible exception of Ca and Sr, trends in chemical element concentrations in inner zone wood with tree-ring age did not indicate a response to the effects of timber cutting, chestnut blight or atmospheric deposition.

INTRODUCTION

Tree-ring chemistry has frequently been used to record changes in levels of air pollutants and, more recently, changes in the soil chemical environment. Long and Davis (1989) recently found that Sr concentrations in white oak (*Quercus alba* L.) in Pennsylvania showed a consistent pattern of higher Sr accumulation from fly-ash in xylem for periods when coal-fired emission stacks were lowest and at locations near power plants. Guyette et al. (1989) showed a decrease in heartwood molybdenum concentration in eastern redcedar (*Juniperus virginiana* L.) which was believed to be caused by increased atmospheric sulfur deposition. McClenahen et al. (1989) showed significantly increased chemical element content of tree-rings in yellow-poplar (*Liriodendron tulipifera* L.) in response to applications of N-P-K fertilizer and dolomitic limestone to the soil. Bondietti et al. (1989) used radial trends in the ratios of Al to base cations in red spruce (*Picea rubens* Sarg.) and eastern hemlock (*Tsuga canadensis* (L.) Carr.) wood to infer the impact of atmospheric deposition on

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soil in Tennessee and North Carolina. Sayre (1987) and DeWalle et al. (1990) both showed that the chemical element content of sapwood xylem in several Appalachian tree species varied with soil fertility. All of these papers indicate that tree-ring chemistry has potential to record time trends in environmental pollution.

Despite the successes in the application of tree-ring chemical analysis to assess environmental pollution, interpretation of results can be ambiguous. Lepp (1975) pointed to many uncertainties with regard to pathways of metal uptake, complexation, and lateral transport in trees which limits use of tree-ring chemical chronologies in studies of environmental pollution. For example, McClenahen et al. (1989) found evidence that P, S, K, Ca, and Zn were mobile in yellow-poplar wood. Thus, application of tree-ring chemistry is not an exact science.

This study was initiated to determine if the radial variation of tree-ring chemistry in two mature Northern Appalachian hardwood stands could be used to determine if changes have occurred in the forest chemical environment. Environmental stresses in these stands can be documented and have included early forest cutting, chestnut blight, and relatively high levels of acidic atmospheric deposition. The sites, Fork Mountain and Pea Vine Hill, have differing soil fertility levels (DeWalle et al. 1988) and any trends related to soil changes were emphasized in this paper. Tree species studied were red oak (*Quercus rubra* L.) and black cherry (*Prunus serotina* Ehrh.), both important commercial species.

STUDY AREAS

Trees studied were located on Fork Mountain at Fernow Experimental Forest in northcentral West Virginia (39°, 03'N; 79°, 41', 30" W) and Pea Vine Hill on Laurel Mountain in southeastern Pennsylvania (40°, 10', 45" N; 79°, 09' W). Fernow Experimental Forest is located near Parsons, WV and is managed by the U. S. Forest Service, Northeastern Forest Experiment Station. The Pea Vine Hill site is part of Rolling Rock Farms near Ligonier, PA. Both sites were gently sloping (<10% slope) ridge-top sites.

The Fork Mountain site was dominated by red oak, black cherry, and sugar maple (*Acer saccharum* Marsh.) trees with minor amounts of other hardwoods occurring in the overstory. Soils were derived from sandstone and siltstone from the Catskill and Chemung formations. Soils were Dekalb and Berks series loamy-skeletal, mixed, mesic, Typic Dystrochrepts. Elevation of this site was about 850 m. Mean annual precipitation at the Fernow Experimental Forest is 142 cm and mean annual air temperature is 8.9 degrees C.

At Fork Mountain heavy high-grade cutting occurred in 1910-15. In addition, residual American chestnut (*Castanea dentata* (Marsh.) Borkh.) trees began to die from chestnut blight in 1910 and by 1925 all mature trees were killed. Salvage logging of dead American chestnut occurred in this stand at about this time.

The Pea Vine Hill site consisted of red oak and black cherry trees almost exclusively. Sandstone and shale from the Pottsville and Mauch Chunk Formations, respectively, were found in soil pits at the site. Soils were Hazleton loamy-skeletal, mixed, mesic Typic Dystrochrepts and Leck Kill fine-loamy, mixed, mesic Typic Hapludults. Elevation of this site was about 880 m. Mean annual precipitation on top of Laurel Mountain near Pea Vine Hill is about 135 cm with 278 cm of annual snowfall depth. Mean annual air temperature is 7.2 degrees C. Forest cutting on Pea Vine Hill has been prohibited since the tract was purchased for Rolling Rock Farms on November 18, 1916. Some dead American chestnut was removed in the 1940-50 period and thus it is assumed that chestnut died in this stand beginning around 1910-15.

Soil at Fork Mountain showed lower acidity and higher exchangeable base cations than soil at Pea Vine Hill. Exchangeable calcium at Fork Mountain averaged 0.82 meq/100 g compared to 0.59 meq/100 g at Pea Vine Hill (DeWalle et al. 1988). Soil water at Pea Vine Hill exhibited significantly higher H, Mn, and Al and lower Ca and Mg concentrations than at Fork Mountain. More complete soil and soil water chemistry at these two sites is available elsewhere (DeWalle et al., 1988).

Atmospheric deposition is relatively acidic at both sites. Out of 82 wet deposition monitoring stations in the United States, the Leading Ridge, Pennsylvania station which is located 130 km northeast of the Pea Vine Hill site ranks 1st in deposition of H^+ and 6th in sulfate deposition (Knapp et al. 1988). The Parsons, West Virginia station within 20 km of Fork Mtn. ranks 9th in H^+ and 10th in sulfate deposition.

METHODS

Five red oak and five black cherry trees were sampled at both the Pea Vine Hill and Fork Mountain sites in 1985. Trees selected for coring were dominant and co-dominant overstory trees with relatively straight boles and healthy crowns within about 500 m of ridge-top soil leachate monitoring sites used in other research. No hollow trees were sampled. Some of the red oak trees sampled at both sites had pith ages over 100 years; these trees apparently survived the heavy cutting in 1910-15 at Fork Mtn. Other red oak and all black cherry trees sampled had pith ages of 85 years or less. Diameters at breast height of sampled trees at Fork Mountain averaged 57 cm for red oak and 48 cm for black cherry. Diameters at Pea Vine Hill averaged 44 cm for red oak and 41 cm for black cherry.

Wood cores were extracted from tree boles at breast height using a 4-mm diameter Teflon-coated increment borer. Borers and extractors were cleaned with acetone and deionized water prior to each field visit and rinsed with deionized water before each extraction. Four cores from bark to pith were extracted from each tree. Cores were extracted at approximately 90-degree angles from each other around the circumference of the trees. Samples included any reaction wood present. No cores with diseased tissue were analyzed. Plastic gloves were used whenever cores were handled. Cores were rinsed with deionized water after extraction in the field and transported from the field and frozen in plastic straws.

In the laboratory, cores were divided into five-year growth increments and the segments of the four cores from each 5 yr segment were composited for each tree. Cores were not cross-dated before compositing. Errors could exist due to missing or indistinct rings when comparing the ages of 5 yr segments among trees and sites. Any such errors are more likely in black cherry with diffuse-porous wood and relatively indistinct rings than in red oak with ring-porous wood and more distinct rings. Composite samples were used to reduce sample variability and provide sufficient mass for chemical analysis. Length of each core segment was measured with a calipers and averaged for each composite sample. Composite sample dry weights averaged 0.7 g with a range from 0.11 to 1.91 g. The division between sapwood and heartwood in the cores was not recorded.

Wood cores were analyzed for phosphorus, potassium, calcium, magnesium, iron, manganese, molybdenum, copper, zinc, sodium, aluminum, silica, cobalt, chromium, nickel, lead, cadmium, strontium, and barium at the University of Georgia, Institute of Ecology using a Jarrel-Ash plasma emission spectrometer. Cores were oven dried, weighed, ashed and digested in 20% nitric acid prior to analysis (Jones 1977).

Multiple regression analysis was employed to analyze trends in tree-ring chemistry data for each element, species, and site. Tree-ring chemical concentrations were used as dependent variables and independent variables were ring age in years, basal area increment in mm^2 per five years, and a piecewise regression term which is described later. Basal area increments were computed from the mean lengths of five-year tree core segments. Serial correlation of residuals from these models, as determined using the Durbin-Watson statistic, was eliminated using an iterative procedure involving differencing all variables over time and using a fitted autocorrelation coefficient (Neter et al. 1985). All statistical tests were conducted at a 95% confidence level.

RESULTS AND DISCUSSION

Basal Area Growth of Trees

Radial patterns of basal area growth for the trees showed peak basal area increments occurred at different times among sites and species (Figure 1). Older red oak trees at both sites experienced rapid diameter growth beginning in about 1910-20 with greatest basal area increment in the 1930-40 period. Release from competition by cutting and chestnut blight probably explains this growth pattern. Younger red oaks and black cherry showed peak basal area increment around 1960 or a gradual increase in basal area increment up to the time of sampling. These younger trees reached breast height after 1910-20 and many are still growing vigorously. As indicated in Figure 1 black cherry trees were generally younger than the red oaks and the youngest black cherry were found at Pea Vine Hill.

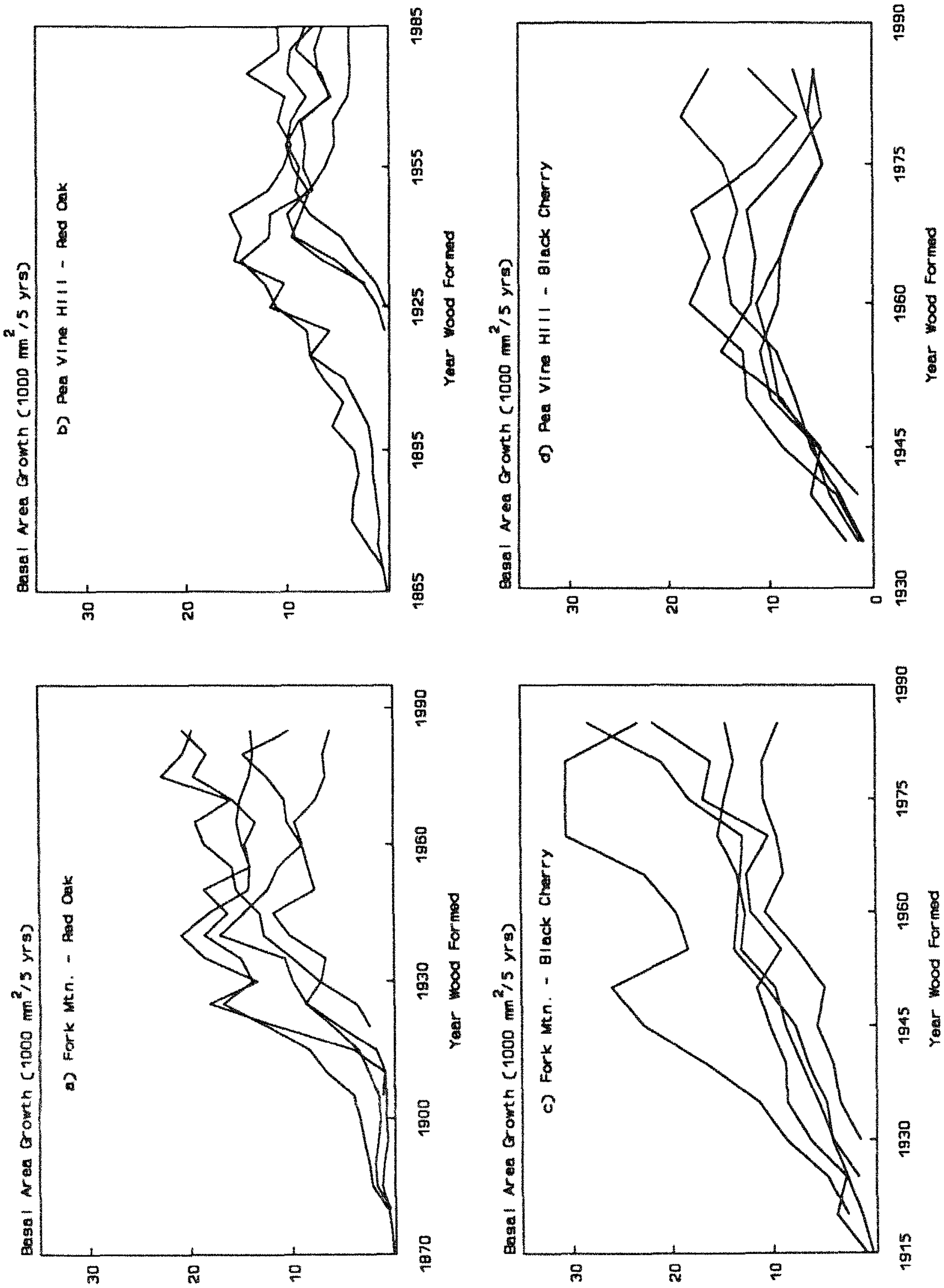

Figure 1. Basal area growth rates of (a) Fork Mtn. - red oak, (b) Pea Vine Hill - red oak, (c) Fork Mtn. - black cherry and (d) Pea Vine Hill - black cherry trees.

Radial Patterns in Tree-ring Chemistry

Distinct patterns of radial variations in the concentrations of chemical elements were found in tree-rings for both sites and species. Patterns observed varied with the element in question.

A pattern of radial variation in tree-ring element concentration was identified in which concentrations varied between an inner and outer zone. In the inner zone concentrations were relatively constant. In the outer zone concentrations increased sharply as the cambium was approached. This pattern of variation was designated Type 1. Designation of inner and outer zones does not necessarily represent heartwood and sapwood zones in these trees. Elements showing Type 1 variation were Ca, Mg, Sr, Ba, Mn, K, and P. Examples of this type of variation are given in Figure 2 for Ca in red oak and black cherry at both sites. Higher concentrations of Ca occurred near both the pith and the cambium in the older red oaks; the absolute maximum occurred near the cambium in the last increment in almost every case. Minimum concentrations in the older red oaks tended to occur during the 1910-50 period suggesting a growth rate effect on concentration for all alkaline earth metals including Ca. Potassium and phosphorus were also classed as Type 1 elements even though they are not alkaline earth metals.

Several features of the Type 1 variation suggest a growth rate effect on chemical element concentrations in tree-rings. Minimum concentrations occur at about the time of maximum basal area increments at least for the older oak trees. Concentrations also increase and basal area increments generally decrease as the cambium is approached. Both of these trends suggest an inverse relationship between concentration and basal area increment. The importance of this relationship was tested with regression analysis since growth rate effects must be removed to detect any trends in chemical element content over time.

The other extreme in radial pattern in tree-ring elements was designated Type 2 with extreme variability and general lack of any radial trend within trees. Elements which followed this Type 2 pattern include Cd, Pb, Cu, Co, Cr, Ni, and Al. Figure 3 illustrates this pattern for Pb in red oak and black cherry. Although trends in radial Pb are indicated for individual trees, no consistent trends are shown for all trees. This was typical of all the above trace metals. The concentrations of these trace metals did not appear to vary with growth rate or increase in the outer, near-cambium region.

Type 3 radial variation in tree-ring elements was intermediate between the other two types with variable, but gradually increasing, concentrations from pith to bark. No consistent steep increases occurred in the outer zone. Elements falling in this category include Na, Fe, Zn, Mo and Si. Examples of Type 3 radial pattern for Mo is given in Figure 4 for both species and sites. Again trends for some trees may look like Type 1 or 2 elements, but the trend was not consistent among trees or sites. Placement of the elements into one of the three patterns of radial variation was somewhat subjective and regression analysis was used to help quantify relationships.

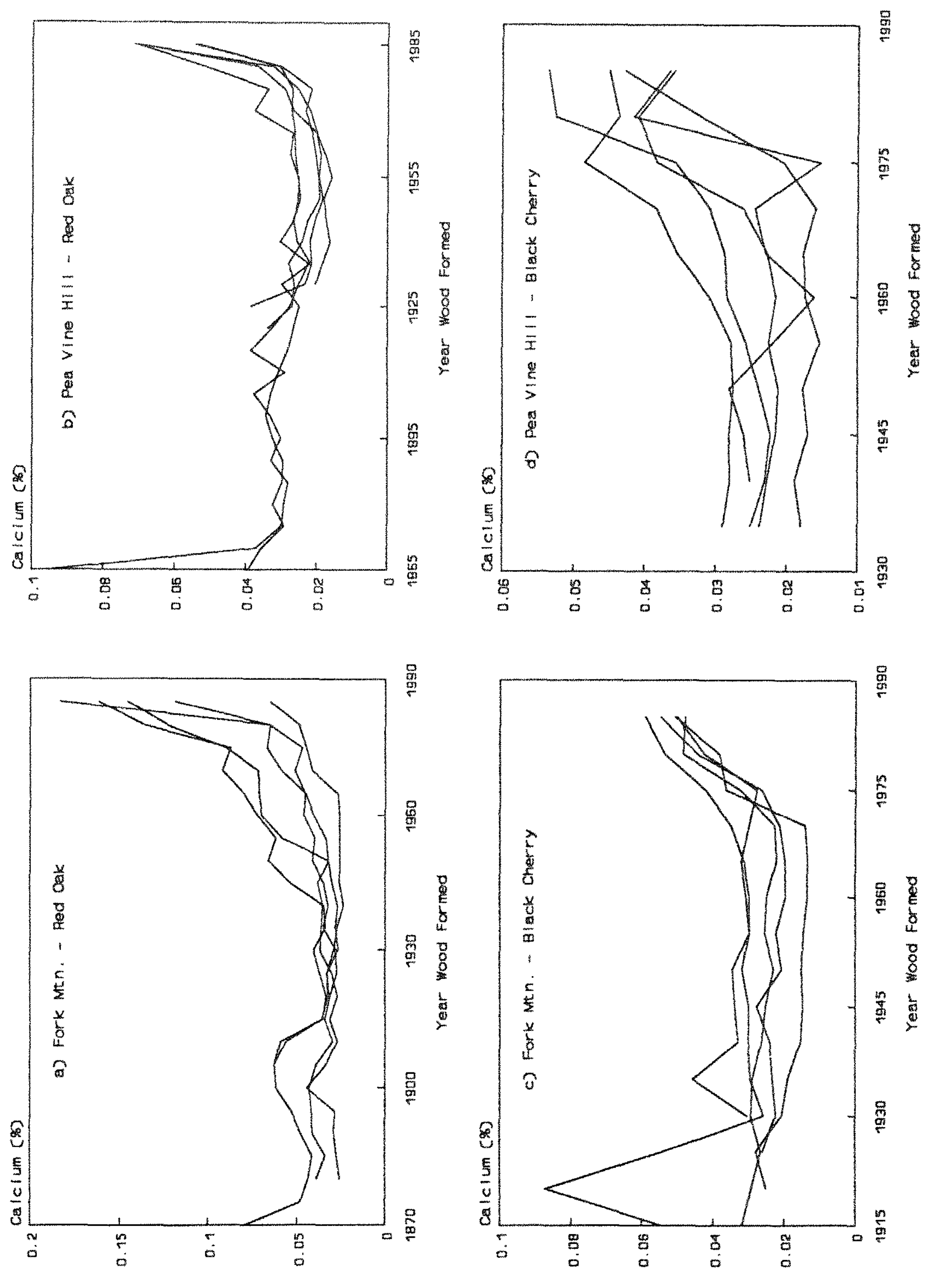

Figure 2. Radial variation of tree ring calcium content for (a) Fork Mtn - red oak, (b) Pea Vine Hill- red oak, (c) Fork Mtn.- black cherry and (d) Pea Vine Hill - black cherry. This pattern of variation was designated Type 1 with a marked increase in the sapwood.

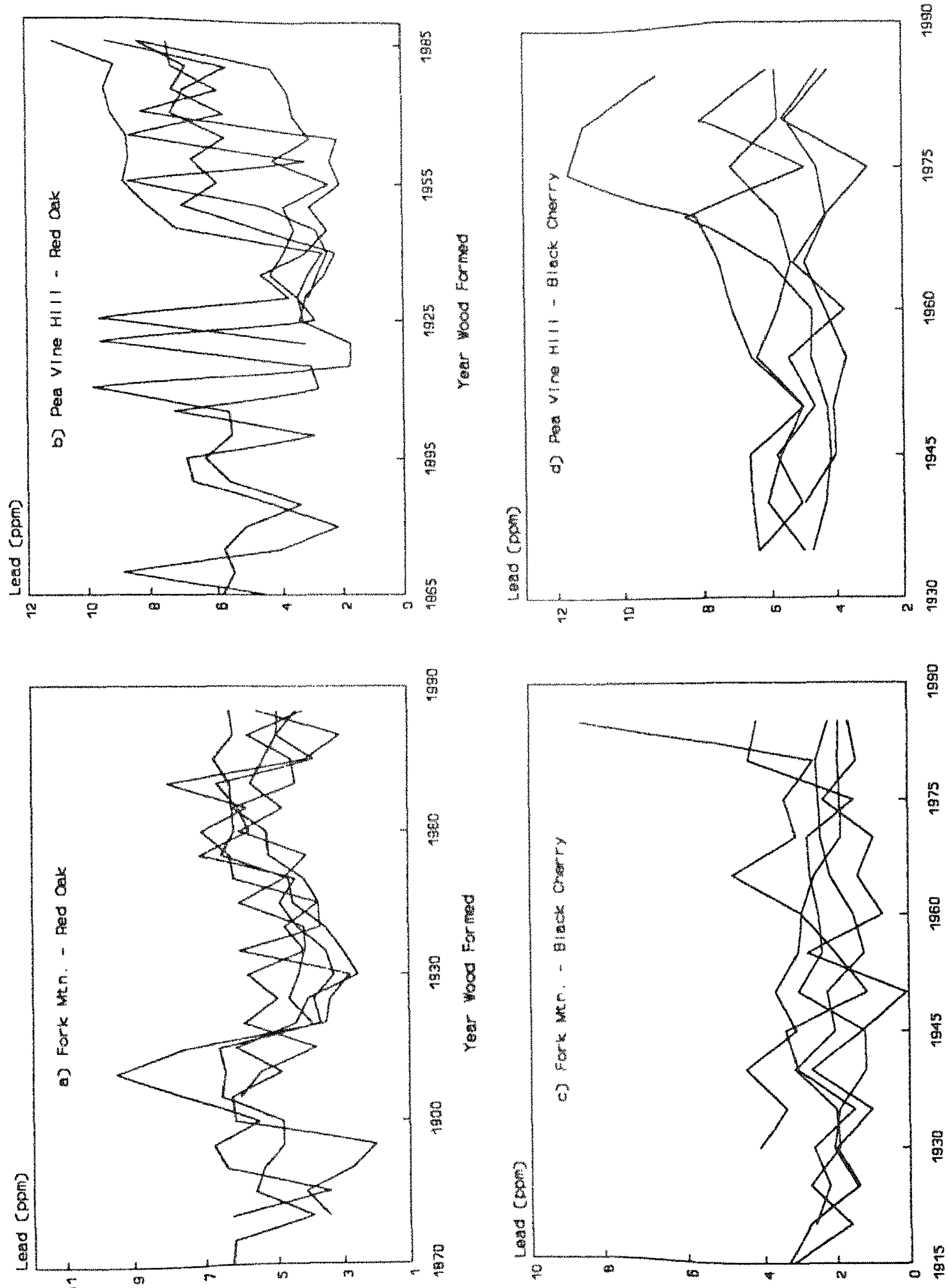

Figure 3. Radial variation of tree ring lead content for (a) Fork Mtn. - red oak, (b) Pea Vine Hill - red oak, (c) Fork Mtn. - black cherry and (d) Pea Vine Hill - black cherry. This pattern with great variation and little radial trend was designated Type 2.

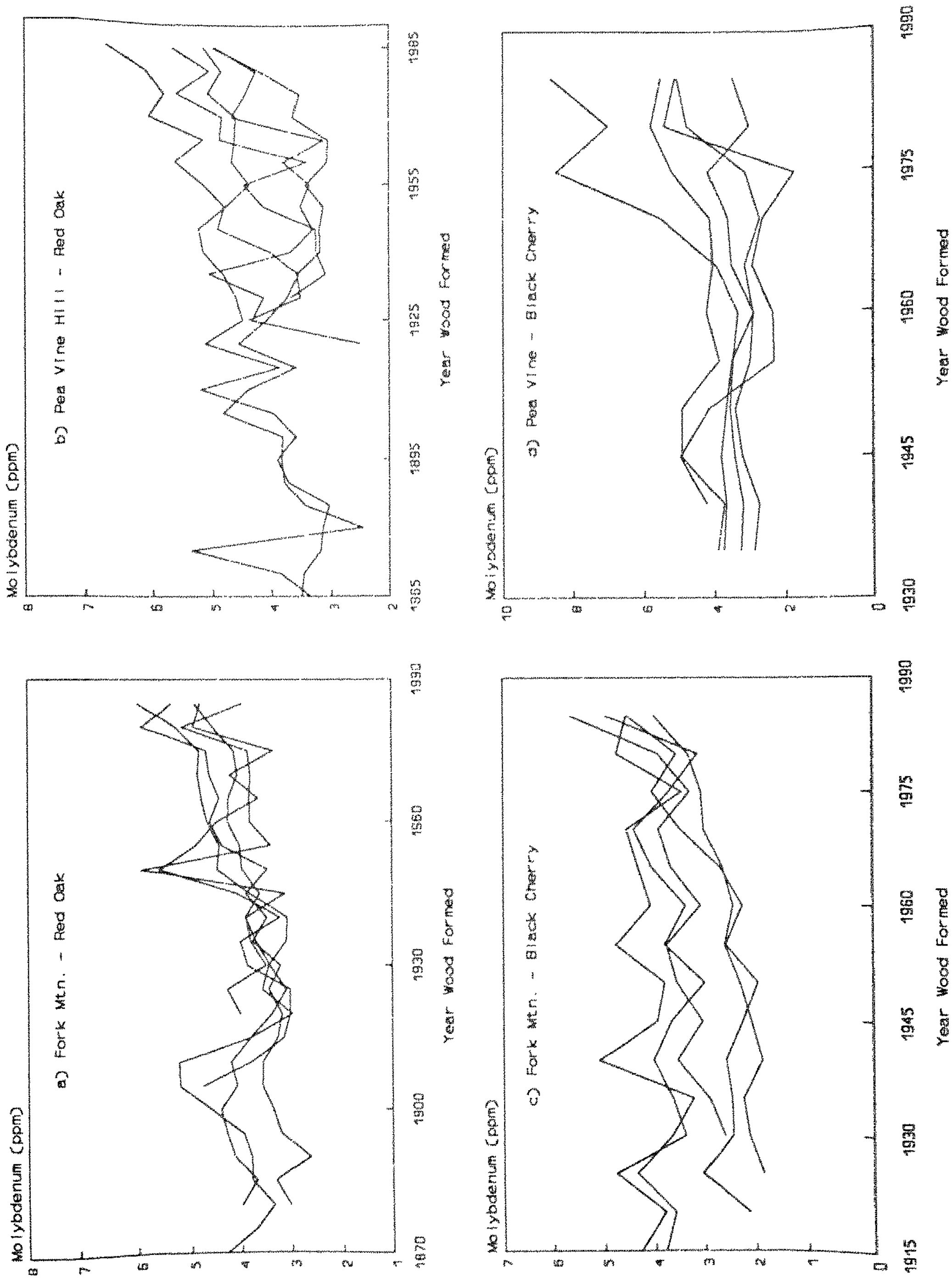

Figure 4. Radial variation of tree ring molybdenum content for (a) Fork Mtn. - red oak, (b) Pea Vine Hill - red oak, (c) Fork Mtn. - black cherry and (d) Pea Vine Hill - black cherry. This intermediate pattern of radial variation was designated Type 3.

The cause of the varying radial patterns among elements can not be determined with certainty at present, but some observations are appropriate. The fact that the same type of radial variation occurred for each element in both species indicates the pattern is closely linked to the nature of the element and not to the considerable difference in wood structure between the ring-porous red oak and diffuse-porous black cherry. Groupings of the elements into the three types of radial variation suggest the cause may be linked to the origin of the elements, e.g. soil vs. atmosphere, or the nature of the element. Type 1 elements were largely bivalent alkaline earth metals which are quite abundant in the soil. Type 2 and 3 elements are primarily trace metals found in the soil and atmosphere. The role radial translocation may have played in shaping the patterns of element variation observed is unknown. Thus, more research is needed to ascertain the true cause of the observed radial variation patterns.

Regression Models of Element Radial Variation

Piece-wise regression models were developed to describe the radial variation in concentration of elements from pith to cambium. Two line segments were used in the piece-wise regression: one for the near-cambium outer region needed for at least Type 1 elements and the second segment for the inner region. The dependence of concentration on growth rate was also included in the models by using basal area increment as an independent variable. The model form used was:

$$Y=b_0+b_1X_1+b_2X_2+b_3(X_2-c)X_3$$

where:

- Y = concentration of element in segment, ppm
- X_1 = basal area increment for tree, $mm^2/5$ yr
- X_2 = age of growth segment, yr
- c = age at inner zone-outer zone boundary, yr
- X_3 = indicator variable, $X_3=1$ if outer, $X_3=0$ if inner zone.

Through trial and error analysis, the best value for the variable c was determined to be 15 years.

Serial correlation existed in the residuals from application of the above model in most cases. Since serial correlation invalidates hypothesis testing relative to the significance of regression coefficients, a method was needed to remove serial correlation. An adaptation of the transformed variable-iterative approach described by Neter et al. (1985) which involves running the regressions using all variables differenced over time with a serial correlation coefficient was used to remove serial correlation in the residuals. Using this procedure regressions are run on transformed variables as:

$$Y_t'=Y_t-rY_{t-1} \text{ and } X_t'=X_t-rX_{t-1}$$

where r is the serial correlation coefficient. The maximum R^2 equation with a non-significant Durbin-Watson coefficient was adopted after iteration on the serial correlation coefficient in increments of 0.2 from r = 1.0 to r = -1.0. Serial correlation coefficients ranging between -0.2 and 1.0 were needed to eliminate serial correlation in the model residuals based upon a two-tailed Durbin-Watson test statistic. Results of these regressions run with differenced data are summarized in Tables 1 and 2.

Trends of chemical element concentration with ring age or time in the inner-zone, as indexed by the b_1 coefficient, were highly variable among elements, species and sites. In Tables 1 and 2, a positive b_1 coefficient indicates that concentration increased with time or decreased with ring age. Significant trends in the inner zone were indicated in 21 equations, 14 positive and 7 negative regression coefficients, out of the 76 total equations. Within a species the only consistent trend was an increase in Mo concentrations with ring age for red oak at both sites. This trend is opposite that found by Guyette et al. (1989) in heartwood of eastern redcedar after 1860. Within sites the only consistent trend was an increase in P content with time in both species at Pea Vine Hill.

Trends for Ca with ring age in the inner zone varied between species. At Pea Vine Hill, Ca decreased in red oak and increased in black cherry with time. Release from competition by cutting and chestnut blight would be expected to increase availability of Ca. Atmospheric deposition would probably initially increase Ca availability due to mobile sulfate anions in the soil solution and later deplete Ca if the site fertility were low. Pea Vine Hill soil was less fertile than that at Fork Mtn. Increases of Ca with time in black cherry at Pea Vine Hill would more likely be a response to increased atmospheric deposition, since effects of release would be minor by 1935 when these young black cherry reached breast height. Older red oak at Pea Vine Hill showed a general decline of Ca with time in this inner wood zone. Alone, this trend might be taken to indicate general depletion of Ca from the soil by atmospheric deposition. The opposite trend in black cherry for at least the latter part of this time interval confuses the issue and may indicate species differences in accumulation of Ca in bole wood.

Differences in time trends for Sr were also found between species in inner zone wood at Fork Mtn. Strontium increased in red oak and decreased in black cherry at Fork Mtn. These trends are opposite those found for Ca in each species at Pea Vine Hill and may be related to the competition between Sr and Ca in biological systems. However, no significant trends were indicated for either Sr at Pea Vine Hill or Ca at Fork Mtn. to substantiate this relationship.

Other significant changes of element concentration with ring age were not duplicated at either site or for either species. Type 3 elements which were identified with general increases in concentration with ring age based upon visual inspection, did exhibit the majority of positive inner-zone ring age trends.

Variation of element concentration with basal area increment was almost always negative (negative b_2). In 17 out of 20 equations in which the b_2 coefficient was significant, the sign of the coefficient was negative. Negative correlations between element concentration and basal area increment were found for all types of elements. Thus, element concentration

Table 1.--Red oak regression analysis summary for Fork Mtn. and Pea Vine Hill based upon differenced data and use of serial correlation coeffcients.

	Fork Mtn.				Pea Vine Hill			
Element	R^2	b_1	b_2	b_3	R^2	b_1	b_2	b_3
Type 1								
Ca	42	-	N[2]	P	35	N	-	P
Mg	61	-	-	P	85	-	P	P
Sr	36	P	N	P	24	-	N	-
Ba	ns[1]	-	-	-	32	N	N	-
Mn	61	-	-	P	34	-	-	P
K	35	-	N	P	13	P	-	P
P	77	-	-	P	70	P	-	P
Type 2								
Cd	ns	-	-	-	ns	-	-	-
Pb	ns	-	-	-	ns	-	-	-
Cu	19	P	N	-	ns	-	-	-
Co	13	-	N	-	ns	-	-	-
Cr	ns	-	-	-	ns	-	-	-
Ni	18	P	N	-	ns	-	-	-
Al	13	-	N	-	ns	-	-	-
Type 3								
Na	21	-	N	P	ns	-	-	-
Fe	20	-	-	P	30	N	-	-
Zn	ns	-	-	-	28	-	N	-
Mo	30	P	N	P	13	P	-	-
Si	ns	-	-	-	ns	-	-	-

[1]ns = non-significant model, see text.
[2]N = negative trend with time.
P = positive trend with time.
\- = no significant trend.

Table 2.--Black cherry regression analysis summary for Fork Mtn. and Pea Vine Hill based upon differenced data and use of serial correlation coeffcients.

	Fork Mtn.				Pea Vine Hill			
Element	R^2	b_1	b_2	b_3	R^2	b_1	b_2	b_3
Type 1								
Ca	19	-	-	P	30	P	N	P
Mg	ns[1]	-	-	-	63	P	N	P
Sr	27	N[2]	-	-	24	-	-	P
Ba	24	N	-	-	24	-	N	P
Mn	30	-	-	P	12	-	-	P
K	47	-	-	P	ns	-	-	-
P	70	N	-	P	70	P	N	P
Type 2								
Cd	ns	-	-	-	20	-	-	N
Pb	ns	-	-	-	ns	-	-	-
Cu	ns	-	-	-	ns	-	-	-
Co	20	N	P	P	ns	-	-	-
Cr	ns	-	-	-	ns	-	-	-
Ni	ns	-	-	-	ns	-	-	-
Al	ns	-	-	-	ns	-	-	-
Type 3								
Na	15	P	N	-	ns	-	-	-
Fe	ns	-	-	-	19	P	-	-
Zn	21	-	P	P	40	P	-	P
Mo	ns	-	-	-	ns	-	-	-
Si	ns	-	-	-	24	P	-	-

[1]ns = non-significant model, see text.
[2]N = negative trend with time.
P = positive trend with time.
\- = no significant trend.

generally decreased as basal area growth rate increased. Similar negative correlation between ring widths and element concentration were found by Ragsdale and Berish (1988) for hickory (*Carya* spp.).

Analyses were also conducted using chemical element loads or xylem accumulation rates, computed as the product of concentration and weight of the five year core increments (Baes and McLaughlin 1984), as the dependent variable. This analysis approach did not eliminate growth rate effects. Since use of loads did not simplify the regression models, the analysis based upon concentrations and basal area increment was employed. It is clear that whatever form of dependent variable is used, growth rate effects must be considered when analyzing tree-ring chemical element time series.

Increases in the concentration of elements with time in the outer zone (positive b3) were commonly significant for both Type 1 and 3 elements, as expected. The regression coefficient b3 was significant in 28 out of 76 total equations; with b3 exhibiting a positive sign in 27 equations. Thus, element concentration increases in the outer zone were significant even after the effects of reduced basal area growth rates in this zone were removed. It is hypothesized that sap flow and cation exchange within the near-cambium xylem elements (Bondietti et al. 1989) is primarily influencing concentrations in this outer zone.

CONCLUSIONS

Distinctly different radial patterns of chemical element concentrations occur from pith to bark among elements regardless of species tested or site sampled. These patterns appear related to the nature of the elements and perhaps pathways for elements to reach the bole wood. Piece-wise multiple regression models with corrections for serial correlation were developed to describe radial chemical element concentration patterns. High concentrations of elements were generally associated with periods of low basal area growth. Chemical element concentrations also increased linearly as the cambium was approached in an outer zone of wood of 15 years width. With the possible exception of Ca and Sr, trends in chemical element concentrations with tree-ring age in the inner wood zone did not appear to be related to impacts of timber cutting, chestnut blight and atmospheric deposition.

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FACTORS AFFECTING TEMPORAL AND SPATIAL SOIL MOISTURE VARIATION IN AND ADJACENT TO GROUP SELECTION OPENINGS

W. Henry McNab[1]

Abstract: Soil moisture content was intensively sampled in three, 1-acre blocks containing an opening and surrounding mature upland hardwoods. Openings covering 0.19-0.26 ac were created by group-selection cutting, and they were occupied by 1-year-old trees and shrubs. During 1989, soil water content at each site decreased rapidly during the summer and did not increase until evapotranspiration declined near the end of the growing season. During wet periods, when weekly precipitation exceeded potential evapotranspiration, soil moisture was about the same in openings as under the trees. In dry periods, soil moisture was greater (1) in the openings than in the adjacent stand and (2) on concave-shaped than on convex-shaped areas. In openings, soil water increased with distance from the edge during dry periods but not during wet periods. Prediction equations based on these site variables and an expression of point-to-point variation in soil water-holding capacity explained over 60 percent of the spatial variation in soil water content during dry periods. Soil water-holding capacity was the most important variable in all prediction equations during both wet and dry periods, accounting for about 23% and 39%, respectively, of the variation in soil moisture. These results suggest that spatial variability in soil moisture in group selection openings is associated with relatively few stand and site variables.

INTRODUCTION

Regeneration by group selection creates small (<1 acre) openings in the forest canopy within which environmental conditions can vary widely (Smith 1962). Compared with our knowledge of environmental conditions in large openings, such as those made by clear cutting, we know little about conditions in small openings. Information gathered in large openings cannot be applied to small openings because of differences in the ratio of area to edge and because of gradients in light and soil moisture caused by the stand boundary. While both light and water influence the response of regeneration in openings (Godman and Krefting 1960, Geiger 1965, Minckler et al. 1973), the soil water regime has received less attention than light. Additional information on variation of soil moisture in openings during the growing season and within sites is needed to better understand the growth response of regeneration. In the present study, I measured temporal and spatial variation in soil water in and around openings of 1/5 to 1/4 acre in a mature hardwood stand during the growing

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season. My purpose was to determine the relative importance of soil, tree stand, and topographic factors on spatial variations in soil moisture.

METHODS

Study Area

This study was conducted in the Bent Creek Experimental Forest, a 6000-acre research facility maintained by the USDA Forest Service in western North Carolina, about 10 miles southwest of Asheville. The Forest is in the Blue Ridge Physiographic Province, whose geology is dominated by granites, gneisses, and schists. Winters are short and mild, and summers are long and warm. Annual precipitation, which averages about 46 inches, is evenly distributed during the year with little occurring as snow. Precipitation generally increases with elevation due to local orographic effects.

The study was installed in the Boyd Branch drainage, at the lower end of a large, east-facing cove at an elevation of about 2500 feet. The cove contains a variety of sites ranging from shallow concave drains to low convex ridges. It is dominated by mesophytic species, including yellow-poplar (*Liriodendron tulipifera* L.), northern red oak (*Quercus rubra* L.), and red maple (*Acer rubrum* L.) trees and an understory of flowering dogwood (*Cornus florida* L.) and sourwood (*Oxydendrum arboreum* (L.) DC). Scattered sweet birch (*Betula lenta* L.) and white oak (*Q. alba* L.) are also present. Steeper side slopes of the cove are dominated by chestnut oak (*Q. prinus* L.) and an understory of mountain laurel (*Kalmia latifolia* L.). This 40-acre cove stand is being regenerated by the group selection method.

During late 1987 and 1988, trees were harvested to create 14 small openings ranging from 0.1 to 0.4 acre in area. Improvement cutting and thinning were done in the timber stand between the group selection openings. Logs were skidded with a small farm tractor equipped with a winch. Logging was restricted during wet weather to reduce soil compaction and erosion. Site preparation in the openings consisted of felling all vegetation over 4.5 feet tall. When the study was initiated in June 1989, each opening was fully stocked with 1- to 2-year-old herbaceous vegetation, shrubs, tree seedlings, sprouts, and advance regeneration that had responded to removal of the overstory.

Soils in the stand are mapped as a complex of Tusquitee, Tate, and Brevard. Tate and Brevard are fine-loamy, mixed, mesic, Typic Hapludults. Tusquitee is a coarse-loamy, mixed, mesic, Typic Dystrochrept. All three soils are mixtures of alluvium and colluvium, and all have surface horizons over 6 inches thick and solums over 40 inches deep.

Plot Establishment and Measurements

Three openings, spaced from 500 feet to 900 feet apart and ranging in size from 0.18 to 0.26 acre, were selected for study. Each opening represents a distinct landform: a small cove branching off the main cove, a low ridge, and a midslope that is linear rather than convex or concave. A square, 1-acre block was defined around each opening. A grid of 25 sample points (spaced at 50x50 feet) was located in each block for soil moisture determination. Total volumetric (in^3water/in^3soil) moisture content was determined by time-domain reflectrometry (TDR) (Topp and Davis 1985) using a Tektronix Model 1502 portable cable tester. Moisture content in the top 6 inches of soil was estimated using a pair of permanently placed 0.125-inch-diameter stainless steel welding rods spaced 2 inches apart and set flush with the soil surface. TDR methods are nondestructive, accurate, and allow repeated measures of soil moisture over time. Perhaps the most important advantage of TDR over conventional gravimetric methods of soil water estimation is that repeated sampling over time is free of errors normally associated with variations among sample location. An empirical, universal calibration curve was used to convert TDR readings to volumetric water content (Topp et al. 1980). The universal calibration curve was verified by measuring soil water content in the 0-6 inch layer at 10 randomly selected, coincident points by TDR and gravimetric methods. Means (and standard deviations) in soil water estimates by the two methods were nearly identical:

TDR	0.321 (0.030) in^3/in^3
Gravimetric	0.309 (0.031) in^3/in^3

Soil moisture was intermittently sampled eight times, from June to mid-October, on a schedule that allowed as much drying as possible before the next anticipated rainfall.

Seven soil, stand, and topographic variables were measured at each of the 25 points in each 1-acre block:

- Soil variable
  1. Soil compaction (lb/in^2)
- Stand variables
  2. Inside or outside of the opening
  3. Distance from edge of opening (feet)
  4. Basal area (10-factor prism)
- Topographic variables
  5. Aspect (degrees)
  6. Slope gradient (percent)
  7. Land surface shape

Four measures of soil compaction were taken in a square pattern around each sampling point using a Soiltest Model PR-025 Proving Ring Penetrometer (30-degree cone with 1.0 in^2 base area) and averaged. Compaction was determined when soil moisture was near field capacity. Several sample points were shifted slightly to avoid logging access roads. All stand and topographic variables were determined by standard methods and are self-explanatory except for land surface shape. Microsites (0.04 acre area that surrounded each soil sample point) varied in surface shape, ranging from slightly convex to concave. Land surface shape of each microsite was quantified by measuring the terrain shape index (McNab 1989). Means and ranges of the continuous variables measured on the three sites are presented in Table 1.

Table 1.--Mean and range of soil, stand, and topographic variables in the three sites studied.

Variable	Midslope	Cove	Ridge
	------------------------ Mean (min./max.) ----------------------		
Compaction (lb/in^2)	145 (74/236)	124 (54/238)	95 (51/184)
Basal area (ft^2/ac)	44 (0/100)	65 (10/120)	66 (0/120)
Distance from edge of plot (feet)	51 (5/105)	34 (30/40)	32 (5/85)
Aspect (degrees)	68 (9/159)	35 (333/87)	138 (63/193)
Slope gradient (%)	16 (5/26)	31 (16/51)	35 (16/22)
Terrain shape index	.01 (-.05/.19)	.00 (-.09/.12)	.02 (-.09/.24)

Soil moisture can also vary in response to other factors including bulk density, organic matter, and proportions of sand, silt, and clay. An indicator variable, soil water capacity, was determined at each sample point to account for these undetermined properties. This approach is similar to that of Helvey et al. (1972), who determined a factor to "remove the relatively unaccountable variation in moisture content resulting from the soils' ability to retain water against drainage and evapotranspiration." This variable, which I call "soil water capacity", is the amount of moisture in the soil when it is wetted to near field capacity. Values were determined somewhat arbitrarily in early June, 2 days after a 2-day rain. Water capacity values were determined for each of the 25 soil sample points on each 1-acre block (Table 2). Variation in the water capacity factors within 1-acre blocks was relatively wide, with no indication of a consistent gradient. Presence within an opening appeared to have little effect on the values. For example, water capacity values on the ridge ranged from 0.259 to 0.337 over a distance of 50 feet. Average water capacity varied somewhat among sites, as indicated by the means and standard deviations:

Cove	0.269 (0.035)
Midslope	0.286 (0.043)
Ridge	0.307 (0.046)

At near field capacity, soils had slightly greater water-holding capacity on the ridge than in the cove.

Precipitation and air temperature were determined and recorded by an automatic weather station located in the midslope opening. Weekly potential evapotranspiration was determined by the method of Thornthwaite and Mather (1957) using a computer program (Stone 1988).

Table 2.--Soil water capacities in the top 6 inches of soil at 25 sample points on each of three sites. Sample points were arranged in a grid with each row and column spaced 50 feet apart. Underlined sample points are in an opening.

Row	Column 1	2	3	4	5
			Cove		
1	.209	.267	.283	.275	.209
2	.283	.291	.322	.267	.314
3	.274	.299	.209	.275	.275
4	.267	.267	.322	.209	.283
5	.275	.226	.283	.307	.226
			Midslope		
1	.322	.299	.218	.307	.314
2	.267	.314	.259	.307	.242
3	.299	.322	.330	.307	.337
4	.283	.259	.226	.226	.314
5	.251	.209	.242	.345	.359
			Ridge		
1	.322	.291	.352	.291	.330
2	.307	.330	.267	.299	.322
3	.426	.259	.330	.259	.337
4	.366	.185	.291	.306	.259
5	.337	.322	.251	.306	.322

That method of estimating plant water use and evaporation has been criticized as too simplistic, but it is useful in this case for broadly characterizing environmental conditions. Because precipitation is a major cause of temporal variation in soil water content, sampling dates were stratified into two periods, dry or wet. Dry periods were arbitrarily defined as weeks in which potential evapotranspiration exceeded precipitation. In wet periods, weekly precipitation exceeded evapotranspiration.

Data were analyzed in two phases. Effect of the discrete factor (in or out of opening) on soil water was examined by analysis of covariance. Correlation and multiple regression analysis were used to determine the relationship of the continuous site variables to soil moisture content on each measurement date. Since sites were unreplicated, statistical comparisons among sites could not be made. Regression coefficients were tested for significance at the

0.05 level. Those results are omitted from this presentation because of its limited scope. A dynamic local model of soil moisture as a function of time and amount of precipitation was not developed, but such a model has been developed for a nearby region of greater precipitation in the southern Appalachians (Helvey et al. 1972).

RESULTS AND DISCUSSION

Temporal Variation

In 1989, losses of soil water to evapotranspiration generally exceeded inputs from precipitation at Bent Creek from early July through early September (Figure 1). The pattern of precipitation was typical, except for September, when heavy rain associated with a hurricane fell for 2 days. July through early September precipitation in 1989 was about 50 percent above the 44-year normal at Bent Creek Experimental Forest. Soil moisture was sampled during three wet periods and five dry periods:

Wet periods: June 22, 29, October 13
Dry periods: July 10, 18, 28; August 18, September 5

Soil moisture content decreased rapidly during July, as precipitation decreased and evapotranspiration increased, and then leveled off during August (Figure 2). Total soil water content during June was slightly higher in the cove than at midslope or on the ridge site. By mid-July, water contents were almost identical on all blocks. Soil moisture contents in mid-September were about 40 percent below those of early June. Soil moisture began to increase by October, as potential evapotranspiration decreased. A similar trend in seasonal soil moisture content was reported for Coweeta Hydrologic Laboratory by Helvey and Hewlett (1962).

Spatial Variation

During wet periods, there was little spatial variation in soil water content. During dry periods, a typical drying pattern emerged, which was dependent upon several factors. For analysis of spatial soil water data, June 22 was selected as a typical wet period and September 5 as a typical dry period.

Soil Water Capacity. Water capacity values were highly correlated with soil water content during both wet and dry periods, as indicated by the following correlation coefficients:

Wet r=0.48
Dry r=0.63

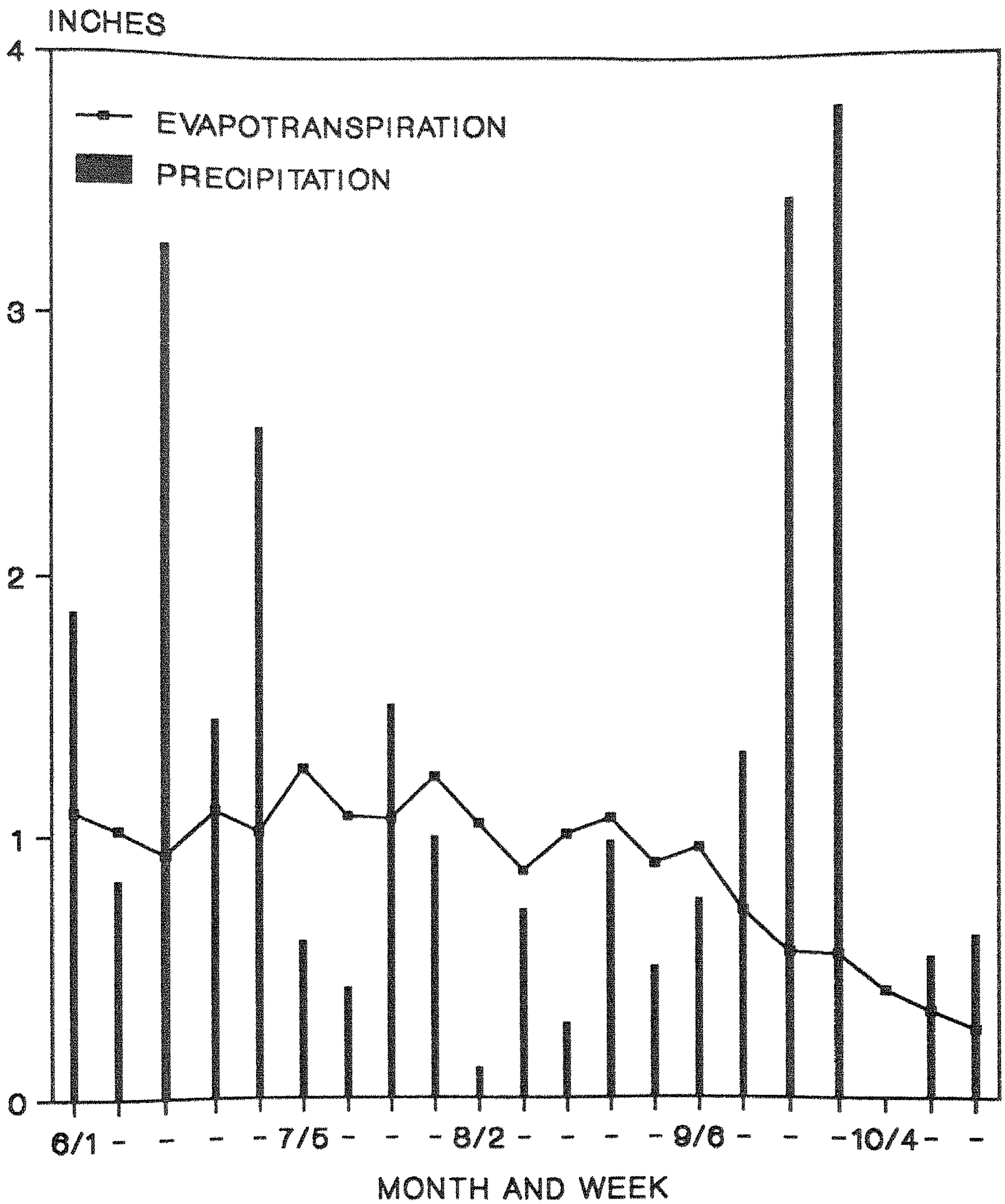

Figure 1. Weekly precipitation and potential evapotranspiration at the midslope site from June 1 to October 4, 1989.

Helvey et al. (1972) reported that a similar variable, which accounted for variation in moisture-holding ability of the soil, was the single most important variable affecting soil water in a study at Coweeta Hydrologic Laboratory.

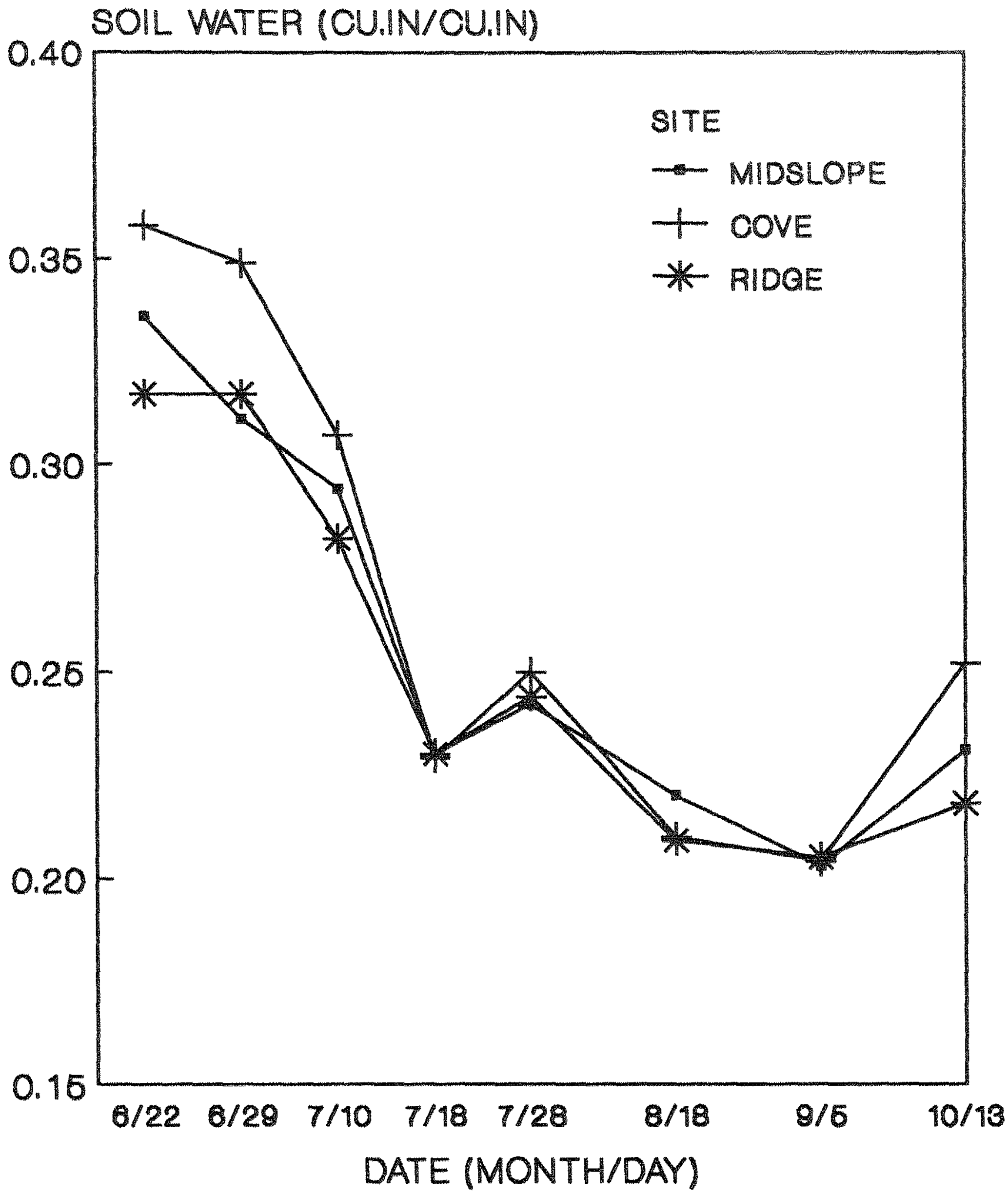

Figure 2. Temporal variation in moisture content of soil on three sites, 1989.

Group Selection Openings. During wet periods soil water content was about the same inside and outside the openings. In dry periods, however, soil moisture was significantly greater inside the openings. The cove site had somewhat greater soil water contents inside openings during dry periods than did the ridge site, with the midslope intermediate between the two (Table 3).

Table 3.--Means and standard deviations () for soil moisture contents in openings and adjacent stands by rainfall period and site.

Site	Inside opening	Adjacent stand	Mean
		WET PERIOD	
Cove	0.351 (.085)	0.349 (.025)	0.349 (.038)
Midslope	0.327 (.028)	0.297 (.042)	0.311 (.038)
Ridge	0.311 (.053)	0.322 (.057)	0.317 (.054)
Mean	0.324 (.052)	0.327 (.044)	0.326 (.047)
		DRY PERIOD	
Cove	0.282 (.059)	0.189 (.041)	0.204 (.055)
Midslope	0.246 (.061)	0.163 (.061)	0.203 (.073)
Ridge	0.214 (.054)	0.197 (.084)	0.205 (.070)
Mean	0.251 (.049)	0.182 (.061)	0.204 (.065)

Soil water content in openings was affected by rainfall period and distance from the edge. During wet periods, no differences in soil water content were evident at sample points in the stand or the opening. In dry periods, however, water content at the edge of the opening was about equal to that in the adjacent stand. Soil water content increased rapidly with distance into the opening (Figure 3) and tended to level off about 30 feet into the opening. These results suggest that trees along the opening boundary influence soil water content mainly through water use by roots. Casual observations revealed that crowns typically extended about 15 to 30 feet into the openings. Minckler et al. (1973) also reported increased soil moisture with distance into the openings.

Although not measured in this study, tree regeneration toward the center of the openings appeared to be taller than that near the edges. Increased light is one reason for better growth, but greater soil moisture is also a likely contributing factor. An application of these findings is that the group selection openings should be large enough so that soil moisture in much of the area is not influenced by the adjacent stand and can be utilized by the regeneration for rapid height growth.

Soil, Stand and Topographic Variables. Soil water content was closely correlated with soil compaction, basal area, and terrain shape index, and somewhat less with slope gradient (Table 4). With the exception of terrain shape index, all correlations were negative. And, except for basal area, the significant variables were correlated with soil moisture in both wet and dry periods.

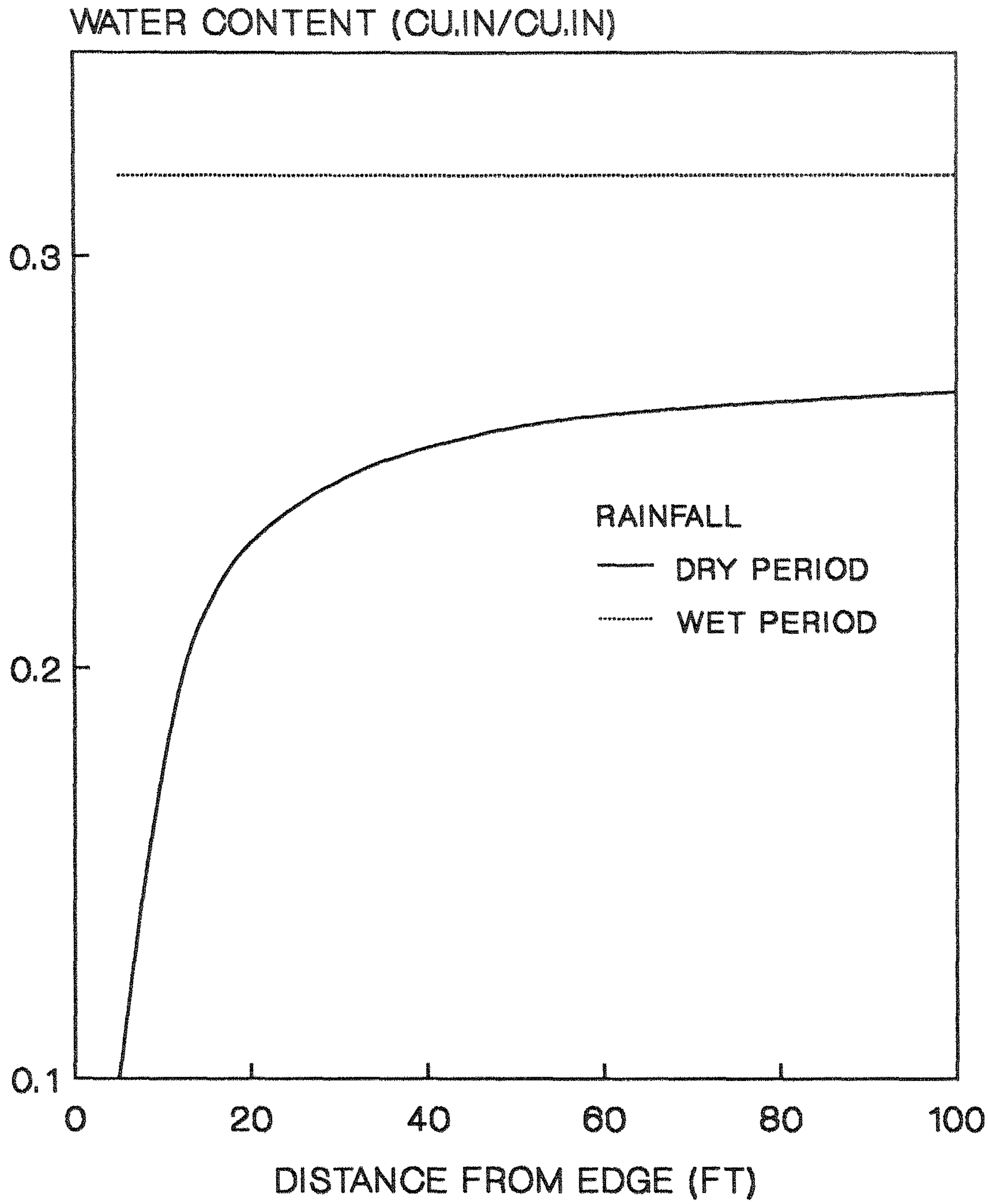

Figure 3. Predicted soil water content in an opening during a dry period as related to distance from edge of opening.

Soil, stand, and topographic variables significantly correlated with soil water content, along with soil water capacity, were included in a multiple regression analysis for the typical sample date during wet and dry periods. The following linear model provided the best fit during dry periods:

$$\text{Soil water (in}^3/\text{in}^3) = b_0 + b_1(\text{soil water capacity}) + b_2(\text{basal area}) + b_3(\text{terrain shape index}) \quad [1]$$

This model accounted for 62 percent of the variation in soil moisture at individual sample points. The soil water capacity was the single most important variable, accounting for 39 percent of the variation. Stand basal area and terrain shape index were about equally important. During wet periods, only the water capacity factors had a significant effect on soil moisture, accounting for 23 percent of the variation.

Table 4.--Pearson correlation coefficients of soil water content with soil, stand, and topographic variables.

Variable	Wet periods	Dry periods
	------------------------ r -----------------------	
Soil water capacity (in^3/in^3)	.46**	.57**
Compaction (lb/in^2)	-.29**	-.36**
Basal area ($ft^2/ac.$)	-.24	-.39**
Aspect (azimuth)	-.09	-.09
Slope gradient (%)	-.10*	-.12*
Terrain shape index	.20**	.37**

* Significant at the 0.05 level.
**Significant at the 0.01 level.

Several variables that were correlated with soil moisture content were not significant in the prediction model because of intercorrelations among variables. Soil compaction was not a significant variable in the model because it was strongly correlated with the soil water capacity (Figure 4). The effect of slope gradient on soil moisture was largely accounted for by terrain shape index. Similar interrelationships between topographic variables have been found in many soil-site studies.

Figure 5 illustrates the response surface of the model for soil water in the 0-6 inch layer on a typical sample date (September 5) during a dry period. Lowest predicted values of soil water content are found on a convex soil surface with high basal area. The model indicates that soil water content approximately doubles when: (1) basal area is reduced from 120 to 0 ft^2/acre with constant surface shape, or (2) soil surface shape changes from slightly convex to concave with constant overstory basal area. If basal area and surface shape change simultaneously, predicted soil water contents are about three times greater in a group selection opening with 0 basal area and a concave surface, compared to a sample point in the adjacent stand with high basal area and a convex shape.

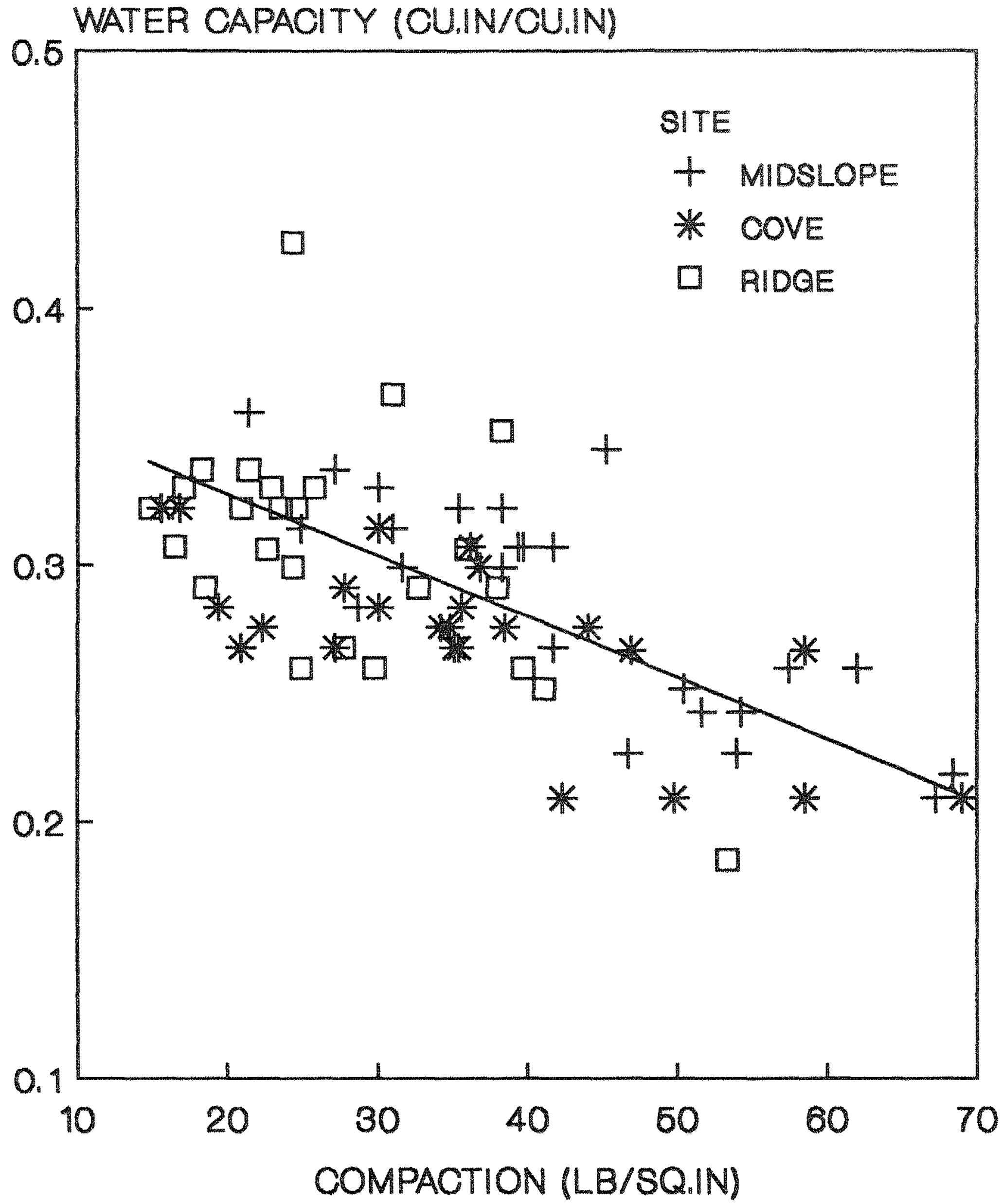

Figure 4. Relationship of soil water capacity to soil compaction, by site and sampling point.

The relationship between soil compaction and soil water capacity may be useful for field application of these results. Field determination of water capacity is time consuming and requires specialized equipment. However, by using a relationship similar to that of Figure 4, the soil water capacity might be estimated from the more easily measured variable, soil

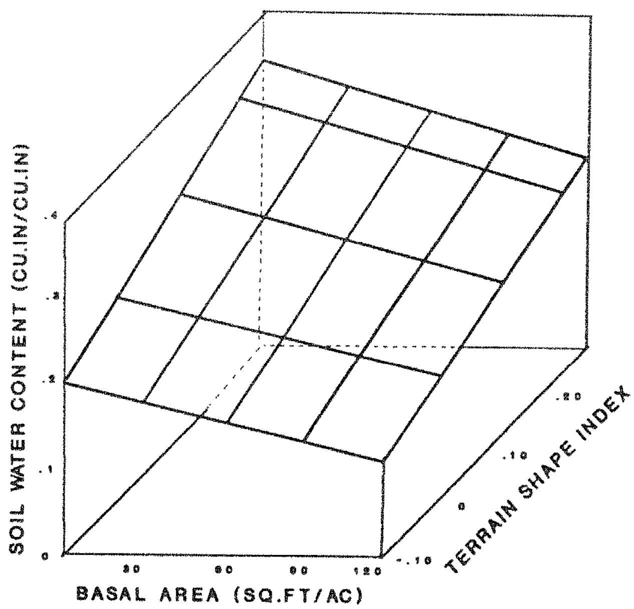

Figure 5. Predicted soil water content as a function of stand basal area and terrain shape index for the 0-6 inch layer on September 5, 1989.

compaction. Another approach would be to reformulate the prediction equation in terms of soil compaction. In any event, water holding capacity of the soil can be estimated with little need for soil sample collection and laboratory analysis.

The effects of temporal and spatial variations in soil moisture on the growth of mesophytic species like yellow-poplar may be quite large. In my own work, I have found an increase in yellow-poplar site index of over 20 feet at age 50 associated with a change in terrain shape from convex to concave. Results of the present study indicate that the effect of terrain shape is probably through additional soil moisture during dry periods. In addition, Beck (1984) reported that a very large proportion of the annual variation in radial growth of individual yellow-poplar trees in the southern Appalachians can be explained by annual variations in rainfall in June and July. He postulated that soils were typically fully charged with moisture early in the growing season, but that supplies sufficient for rapid growth were exhausted by the end of June in dry years. Similar sorts of relationships between soil moisture and growth may also hold for other mesophytic species on well-drained sites.

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RESPONSE OF AN APPALACHIAN MOUNTAIN FOREST SOIL, SOIL WATER AND ASSOCIATED HERBACEOUS VEGETATION TO LIMING

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Abstract: Agricultural limestone was applied in varyious amounts to the surface of three 10-m square forested plots on Pea Vine Hill in Westmoreland County, Pennsylvania; a fourth plot served as a control. Measurements of soil exchangeable calcium and base saturation revealed positive responses to limestone addition on all treated plots. However, percolating soil water (leachate) was not significantly affected up to five months after treatment. Four years after treatment, A horizon exchangeable Ca and base saturation were reduced almost to pre-treatment levels. Response of E horizon soil to limestone treatment was manifested in a doubling of base saturation after two years with a return to pre-treatment values after four years. E horizon exchangeable Ca was also increased but by a lesser amount. Forest floor vegetation responses were highly variable; however, liming increased species diversity.

INTRODUCTION

Current interest in the potential impact of acid deposition on terrestrial ecosystems is in part centered around the long term supply of soil base cations as it relates to increased leaching caused by acid deposition, (Bondietti and Shortle 1990). Many investigators have been attempting to relate observed tree decline symptoms to nutrient depletion. Roberts et al. (1989) reviewed literature related to Type I Spruce Decline and concluded that acid deposition-induced soil magnesium (Mg) deficiencies are a chief cause of these symptoms. They cite several studies that reported reversal of decline symptoms following Mg fertilization. Ke and Skelly (1990) reported Mg deficiencies in a Norway spruce (*Picea abies* (L.) Karst) plantation near the site of this work. Joslin and Wolfe (1989) reported significant correlations between Ca concentrations in northern red oak (*Quercus rubra* L.) roots and leaves and various liming treatments.

Johnson and Todd (1990) and others have recently reviewed Ca depletion on forested sites in relation to leaching by acid deposition. Bondietti and Shortle (1990) and Federer et al. (1989) have concluded that acid deposition has resulted in increased Ca leaching. Based on an analysis of long term soils data at five sites in the eastern U.S., Federer et al. (1989) have estimated Ca leaching rates to be 4-16 kg/ha/yr.

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However, previous work on the fertilization of hardwoods in Pennsylvania is equivocal on this point. Auchmoody (1983) reported increased growth of black cherry (*Prunus serotina* Ehrh.) following N and P fertilization and he further contended (Auchmoody 1985) that Ca was not limiting growth for black cherry in the Allegheny National Forest. Ward and Bowersox (1970) showed increased growth in an oak stand that received both N and Ca applications. Sharpe et al. (in preparation) report increased growth of red oak seedlings after fertilization with bone meal ($CaPO_4$) in a greenhouse study. Fertilizer applications have been shown to be beneficial to the establishment of black cherry following harvesting activity (Auchmoody 1985). The effects of applications of N, K and lime on element fluxes were investigated by Matzner et al. (1983). They concluded that N and K fertilization increased leaching of Al and Mn while liming substantially increased the Ca/Al ratio in soil solution.

In 1983 an investigation of biogeochemical cycling of acid deposition was initiated on Pea Vine Hill in southwestern Pennsylvania. As a part of this effort, 10m x 10m plots were treated with agricultural limestone to determine the impact of calcium (Ca) addition on soil leachate quality. In this study we attempted to determine the impact of lime additions on soil leachate chemistry, soil exchangeable Ca, base saturation, and herbaceous and woody ground vegetation.

METHODS

A description of the study area is given by DeWalle et al. (1988). Instrumentation for the collection of soil leachate samples, leachate analysis and estimation of nutrient fluxes are given by DeWalle et al. (1988) and Swistock et al. (1990). The soil was a Hazelton/DeKalb loamy-skeletal, mixed mesic typic Dystrochrept located on Pea Vine Hill in southwestern Pennsylvania.

Adjacent 10m x 10m plots were established next to an excavated soil lysimeter pit. Suction lysimeters were installed on these plots and pan lysimeters were positioned beneath the plots. Soils in each pit were characterized (DeWalle et al. 1988). One plot (plot #2) was designated as the control and received no limestone. Plots #1, #4 and #5 received bagged agricultural limestone on November 1, 1984 at the rate of 5.9, 11.1, and 2.9 tonnes/ha, respectively in a one-time application. The limestone was applied to the surface of the litter layer by hand. These application rates were designed to produce a buffer pH of 5.5, 7.0 and 1/2 the 5.5 rate, respectively in the A soil horizon. The calculation of limestone application rates was based on the SMP buffer pH (Penn State Soil and Forage Testing Laboratory) of the O, A, and E horizons prior to treatment and the volume of stone free soils in each horizon. The soil in the A and E horizons was estimated to be 30 percent stone. The standard agricultural lime requirements to produce the buffer pH's mentioned, for an initial buffer pH of 5.8 for a soil depth of approximately 17 cm, were adjusted by reducing the lime requirement by 30 percent. The 1986 measurements of A horizon soil pH for the light, moderate and heavy application revealed estimated pH's of 4.0, 6.1, and 5.8, respectively. The control A horizon pH remained near pH 3.8. Consequently, the method used to estimate lime application is in need of further refinement for acid soils.

Two samples were obtained from each soil horizon on each plot. Soil samples were analyzed in the Soil and Forage Testing Laboratory at the Pennsylvania State University for CEC, pH, exchangeable Ca, Mg, P and K and base saturation.

Soil leachate was collected bi-weekly utilizing both zero tension pan and ceramic-cup suction lysimeters. Swistock et al.(1990) contains the details of lysimeter installation, data collection, and laboratory methods. Only E horizon zero-tension data are reported in this paper.

Surveys of forest floor vegetation employed ten randomly selected permanent 1m^2 plots on each 10m x 10m treatment area. All woody and herbaceous stems were counted once prior to treatment and four times after treatment. Surveys were conducted in September of 1984, 85, 86 and 89 and June of 1990.

RESULTS

Soil Chemistry

Limestone applications resulted in increased levels of exchangeable Ca and base saturation in the A and E soil horizons. The greatest increases were in the A horizon soil (Tables 1 and 2). Within two years after surface application of ground limestone, levels of both exchangeable Ca and base saturation increased dramatically; however, within five years of treatment significant declines approaching pre-treatment levels were apparent. Despite these declines, more Ca was present on the treated plots than prior to treatment.

Table 1.--Changes in exchangeable Ca in A and E horizons with time for all plots.

	Plots							
	Control		Low Lime		Med. Lime		High Lime	
Year	A	E	A	E	A	E	A	E
	Ca (meq/100g)							
1983	0.85	0.70	0.75	0.35	0.70	0.60	0.60	0.35
1986	1.45	0.40	3.65	0.62	16.4	0.58	21.0	0.62
1988	0.35	0.30	1.40	0.30	0.98	0.40	1.72	0.30

The precise fate of much of the applied Ca is not known. A portion was most probably taken up by plants growing on the site and is being cycled through the system, with temporary storage in the forest floor and humus. It is also quite likely that Ca has been leached from the root zone by percolating soil water.

Table 2.--Changes in A and E horizon base saturation with time for all plots.

	Plots							
	Control		Low Lime		Med. Lime		High Lime	
Year	A	E	A	E	A	E	A	E
	Base Saturation %							
1983	5.1	7.50	4.75	5.60	5.45	6.55	3.04	5.20
1986	11.47	7.22	21.78	10.82	81.68	10.27	79.32	11.10
1988	2.52	4.00	10.38	5.31	8.55	5.18	9.68	4.88

Soil Water

Soil water was collected beneath the E and B horizons on all plots with zero-tension pan lysimeters for one year prior to lime application and five months afterward. Because of seasonal differences in soil water quality, statistical comparisons of before and after leachate data are for the same five month period (November-May). Table 3 contains a summary of E horizon leachate chemistry before and after lime application. There were no significant differences in Ca concentrations as estimated by the E horizon lysimeters before and after limestone applications or among plots. Al concentrations were not significantly different for any comparisons except the before and after periods on the control plot. In general, there were no consistent differences in these data. Unfortunately, monitoring of soil water chemistry could not be continued beyond the five month period. Because ground limestone dissolves relatively slowly, five months was probably not sufficient to detect an increase in Ca concentration in the E horizon soil water. Marschner et al. (1989) reported that increased Ca was not monitored in leachate at 50 cm depth until six months after liming a sandy soil. However, the fact that E horizon soil exchangeable Ca and base saturation increased is evidence for leaching of Ca from the litter, humus and A horizons.

Forest Floor Vegetation

Changes occurred in herbaceous and woody vegetation growing on the test plots. For some species these changes appeared to be consistent and statistically significant. For others, however, it was difficult to ascertain either trends over time or significant differences among treatments. We have selected some species of greatest interest to management foresters for discussion. These include grass (unspecified), hay-scented fern (*Dennstaedtia punctilobula* Michx.), blueberry (*Vaccinium* spp.), deer tongue grass (*Panicum clandestinum* L.), blackberry (*Rubus* spp.), red maple (*Acer rubrum* L.), black cherry, red oak and chestnut oak (*Quercus prinus* L.).

Table 3.--Mean soil water chemistry at the E horizon depth for all plots before and after liming.

	Plots							
	Control		Low Lime		Med. Lime		High Lime	
Parameter	Before	After	Before	After	Before	After	Before	After
pH	4.37ab[1]	4.75a*[2]	4.64a	4.43a	4.34b	4.39a	4.41ab	4.46a
	(mg/L)							
Ca	2.1a	1.3a	2.0a	1.7a	1.4a	1.7a	1.2a	0.9a
Mg	0.4a	0.3a*	0.6a	0.4b	0.4a	0.4ab	0.4a	0.3ab
K	2.1a	2.6a	0.8b	0.8b	0.9b	1.1ab	0.2c	0.3b
Na	2.4ab	4.4a	3.9a	2.8ab	0.4b	0.6b	0.7b	0.4b
Al	4.5a	2.0a*	2.5a	3.3a	3.2a	3.0a	2.8a	2.5a

[1] Values in the same row followed by different letters are significantly different between plots at $\alpha=0.05$ for the same period.

[2]An asterisk (*) denotes a significant difference ($\alpha=0.05$) for the before and after periods on the same plot.

Some care in the interpretation of the vegetation data is appropriate. For example, although 1985 was the first year following liming, much of the lime remained visible on the forest floor indicating that it was not yet available for plant use. Consequently, 1985 should be viewed as a transition year where the full affect of the treatment was not evident. From 1985 to the present there is an increase in the amount of grass (unspecified) on the limed plots. However, except for 1985, the amount of grass on any limed plot was not significantly different from that on the control. Deer tongue grass (Figure 1) increased from 1986 through 1990 on the plot which received the least lime. On the medium lime plot, deer tongue grass was always greater than the pre-treatment year and on the high lime plot, deer tongue abundance was greater in 1986, 89, and 90. Within year differences were significant between the control and high and low lime plots in 1989 and low lime plot in 1990. There appeared to be an increase in deer tongue grass on the plots receiving the most lime.

Numbers of blueberry on the medium lime plot declined after the 1986 high, but this decline is confounded by an equally steady decline in numbers on the control plot. The relatively low pre-treatment numbers on high and low lime plots also appeared to decline after treatment. None of the within year differences were statistically significant.

Hay-scented fern (Figure 2), a plant that seems to be increasing in prominence in the forests of Pennsylvania, appeared to decline on medium and low lime plots. The high lime plot showed no decrease in fern numbers. Pre-treatment and 1985 fern numbers were not significantly different between the control and medium and low lime plots; however, in 1986 all limed plots had significantly fewer ferns than the control. By 1990, differences between plots were similar to those prior to treatment.

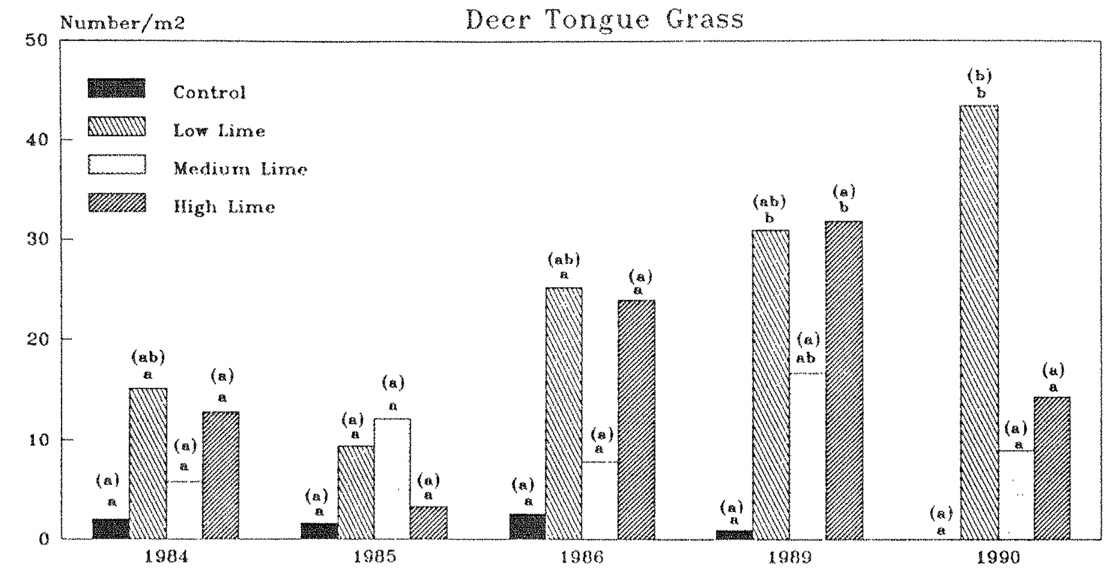

Figure 1. Trends in abundance of deer tongue grass on the control (unlimed) and each limed plot from 1984 to 1990. Different letters above bars indicate a significant difference ($\alpha = 0.05$) within a given year. Different letters in parentheses above bars indicate a significant difference ($\alpha = 0.05$) between years for that plot.

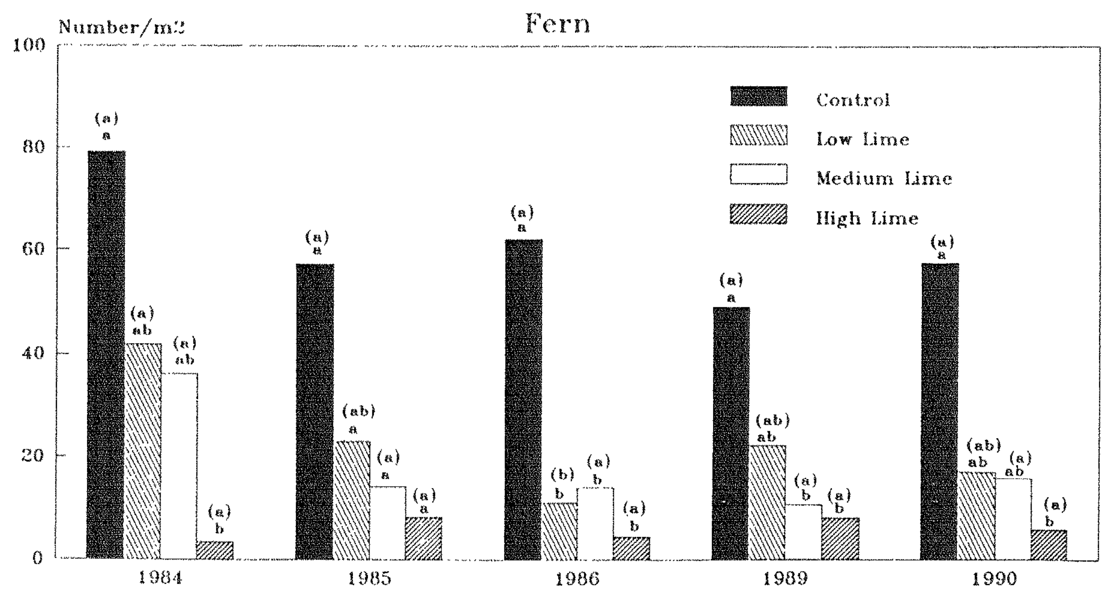

Figure 2. Trends in abundance of ferns on the control (unlimed) and each limed plot from 1984 to 1990. Different letters above bars indicate a significant difference (at $\alpha = 0.05$) within a given year. Different letters in parentheses above bars indicate a significant difference ($\alpha = 0.05$) between years for that plot.

Rubus spp. an important food species for white-tailed deer, appeared to increase on all plots after treatment with the exception of 1986 when no *Rubus* spp. were encountered on any of the plots. Numbers were low in all cases; consequently, there were no significant differences among the plots in any year.

Red maple seedlings did not appear to respond to liming with the exception of 1985, when the low lime plot had significantly more seedlings than any of the other plots. All plots had consistently higher numbers of red maple seedlings after treatment; however, with the exception of 1985, the limed plots and the control were never significantly different. It would appear that red maple did not respond to liming.

The data for black cherry are portrayed in Figure 3. Only the high lime plot appeared to have increased black cherry reproduction following liming. More black cherry seedlings were counted on the low lime plot, but the total numbers were low. Black cherry seedlings did not increase on the control plot.

As can be seen from Figure 4, red oak seedlings were scarce on all of the test plots. Only the medium lime and control plots had any oak seedlings in 1984. No plots had oak seedlings in 1985 and only the medium lime plot had seedlings in 1986. Following an exceptionally good seed crop in the fall of 1989, all plots except the control had oak seedlings in 1990.

A Shannon Diversity Index (Margalef 1968) was computed for all plots for each year that survey data were collected. The diversity of forest floor vegetation increased on the limed plots after 1985, but decreased on the control plot (Figure 5). The indicies computed for all limed plots in 1990 were significantly different ($\alpha = 0.05$) from those for 1984. The control plot index in 1990 was not significantly different from that of 1984.

These plots were not fenced to exclude deer. The area in which the plots were located had a high deer population. During the study, an average of 41 deer were harvested from this 324 ha management unit each year (Fritz, personal communication). With the exception of 1990, all vegetation surveys were done in September. In all years except 1990 every tree seedling was browsed and no seedlings were observed to attain a height greater than 20 cm throughout the course of the study.

DISCUSSION

These limited results, present evidence that addition of ground limestone to the forest floor increased the Ca concentration of soil in the rooting zone. The heaviest applications of lime produced the greatest increases in exchangeable Ca. Within five years after application, exchangeable Ca had returned to near pre-treatment levels in the treated soils. These results are in close agreement with the findings of Marschner et al. (1989) for a limed plot experiment conducted in Berlin, Germany. Plants growing on the plots were undoubtedly involved in removing a portion of this calcium through uptake and cycling through the forest

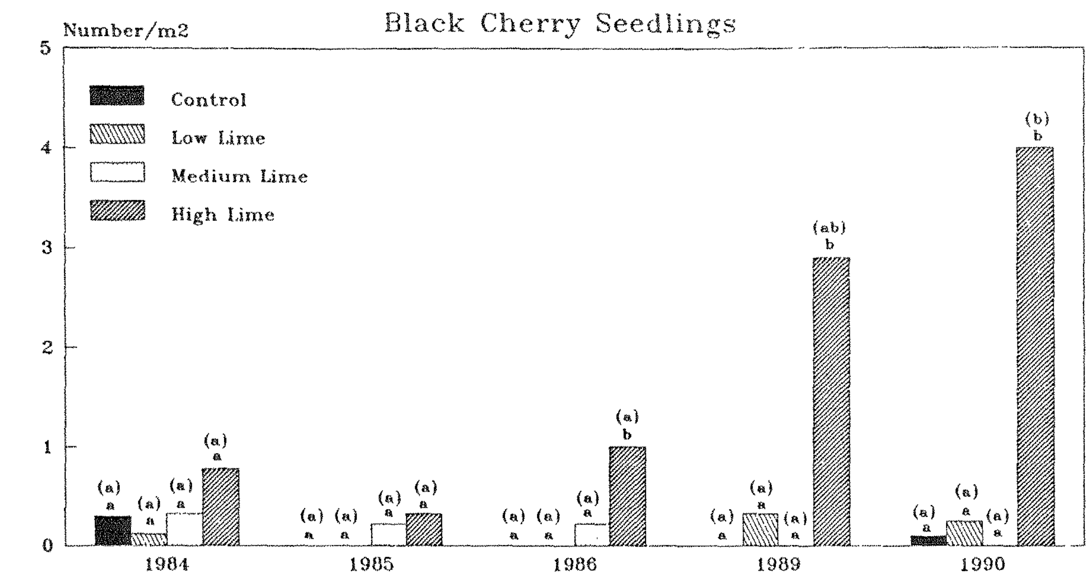

Figure 3. Trends in abundance of black cherry seedlings on the control (unlimed) and each limed plot from 1984 to 1990. Different letters above bars indicate a significant difference ($\alpha = 0.05$) within a given year. Different letters in parentheses above bars indicate a significant difference ($\alpha = 0.05$) between years for that plot.

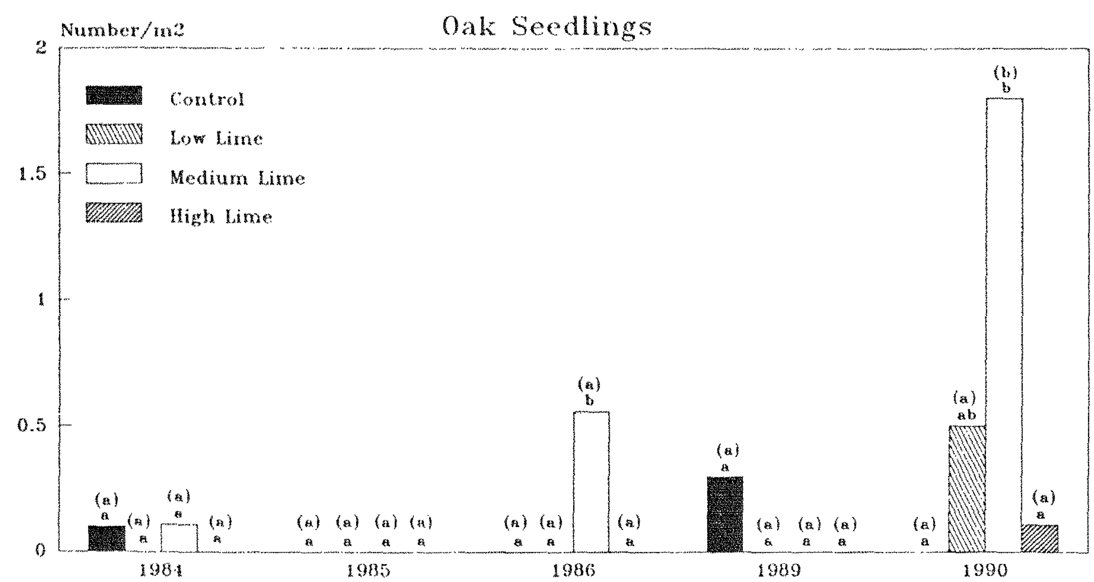

Figure 4. Trends in abundance of oak seedlings on the control (unlimed) and each limed plot from 1984 to 1990. Different letters above bars indicate a significant difference ($\alpha = 0.05$) within a given year. Different letters in parentheses above bars indicate a significant difference ($\alpha = 0.05$) between years for that plot.

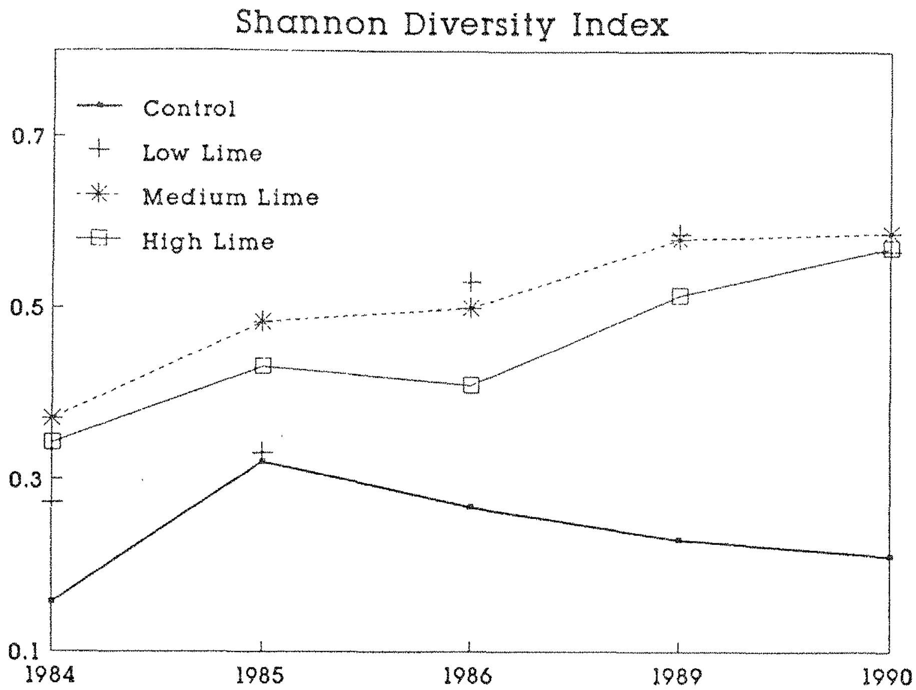

Figure 5. Trends in the Shannon Diversity Index on the control (unlimed) and each limed plot from 1984 to 1990.

floor and humus back to the above ground portions of the plants. Leaching of Ca by percolating soil water also probably contributed to the depletion of the Ca applied to the test plots. Unfortunately, long-term soil water measurements were not made to enable an assessment of the relative importance of these Ca sinks.

Forest floor herbaceous and woody vegetation appeared to respond positively to liming. Species diversity increased on the limed plots as did the numbers of some plant species. Black cherry, deer tongue grass and red oak seedlings all increased significantly in relation to the control plot after liming. Hay-scented fern declined significantly on the plot that received 5.9 tonnes/ha of lime. Other species that declined, but not significantly, were blueberry and red maple. Species increasing in number, but not significantly, were grass and blackberry with the highest numbers generally occurring on the plot that received the heaviest lime application. As mentioned previously, all of these changes occurred despite the presence of large numbers of deer and evidence of considerable deer browsing on the test plots.

SUMMARY

Lime application to several test plots on Hazelton-Dekalb soil located on Pea Vine Hill in southwestern Pennsylvania resulted in increased diversity of plants growing on the plots. Numbers of black cherry seedlings increased and hay-scented fern numbers decreased. Deer tongue grass also increased significantly on the limed plots. Increases in exchangeable Ca in the A horizon of this soil were still evident but approaching pre-treatment levels within five years after liming. Soil water sampling probably did not continue long enough after liming ($\leq$ 5 mo) to detect Ca leaching. In general, the plot receiving the heaviest lime application (11.1 tonnes/ha) showed the greatest overall vegetation response; however, even the plot receiving the lowest application (2.9 tonnes/ha) appeared to demonstrate positive response to liming. It would appear that moderate (5.9 tonnes/ha) or light (2.9 tonnes/ha) lime applications would be sufficient to produce favorable changes in rooting zone soil chemistry. To maintain such changes on this site, additional lime in these amounts would have to be applied at approximately four-year intervals.

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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 tulipfera* 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 ($CaCO_3$) 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 Year (May-April)	Water Yield Change		
	Growing Season[1]	Dormant Season[2]	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
[1] May through October
[2] November through April

Stream Chemistry

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 ($CaCO_3$), 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.

Table 2. Mean annual nutrient concentrations, alkalinity, pH, and specific conductance of streamwater draining the commercial clearcut (LR3) and control (LR1) watersheds before and following harvesting.

Parameter[2]	Pre-Harvest[3]		Post-Harvest Period[1]													
			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
Specific Conductance	50.9	48.1	79.6	34.8*	59.8	42.7*	36.9	32.1	45.9	48.9*	53.3	68.6*	54.2	63.6*	37.4	36.8
pH	6.89	6.91	6.63	6.52*	6.86	6.85	6.64	6.72	6.50	6.72*	6.72	6.98*	6.58	7.00*	6.79	7.01*
Alkalinity	14.6	15.3	15.5	5.5*	19.3	11.0*	6.4	6.7	10.4	14.4*	15.6	26.2*	16.9	23.2*	9.5	10.7
Sulfate	8.39	6.75	7.87	5.55	7.95	5.82	7.16	5.02	7.87	5.83	7.95	7.80*	7.20	6.70*	8.47	6.44
Nitrate	0.03	0.04	0.11	0.40*	0.05	0.28*	0.05	0.14*	0.05	0.12*	0.10	0.10	0.05	0.08*	0.11	0.09*
Calcium	4.43	4.45	5.56	2.49*	6.22	3.58*	2.80	2.50	3.65	4.53	5.52	9.68*	5.87	9.00*	3.37	3.96
Magnesium	2.15	1.72	2.14	1.27*	2.47	1.67*	1.40	1.14*	1.85	1.67*	2.32	2.24*	2.34	2.18*	1.93	1.41
Sodium	0.98	1.02	1.00	0.88*	1.09	0.99*	0.77	0.82	0.85	0.96	1.00	1.22*	1.04	1.24*	0.87	0.80*
Potassium	1.00	0.99	0.93	1.05*	1.01	1.22*	0.96	1.01	0.98	1.07*	0.99	1.01	0.97	1.08*	1.00	1.00

* Significant at 0.5 level

[1] May 1 through April 30 water year

[2] All values except pH and specific conductance are given in mg/L. Specific conductance is given as µS/cm.

[3] October 15, 1973 through September 30, 1976

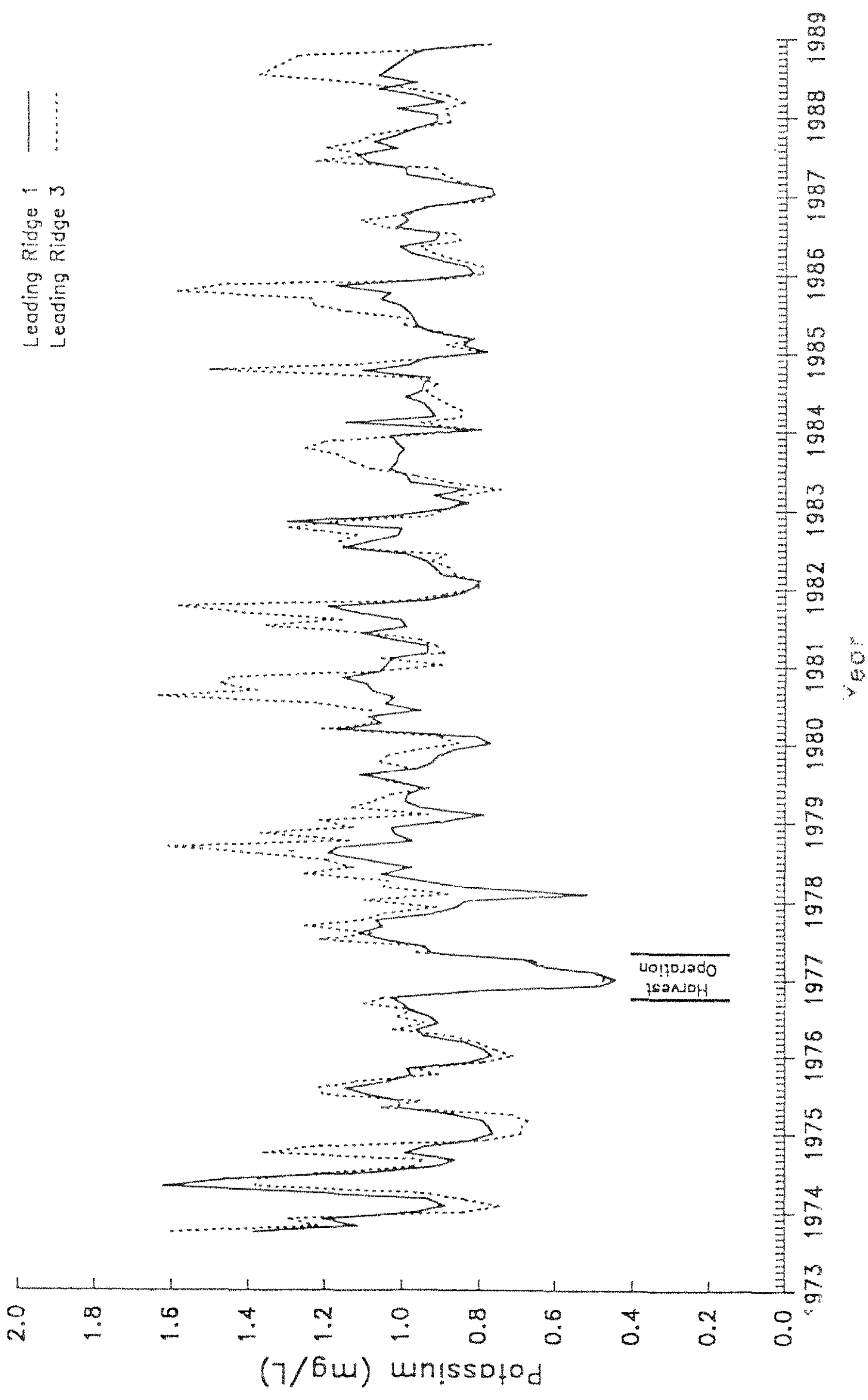

Figure 1. Trends in stream water potassium concentrations for the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977) and after harvesting.

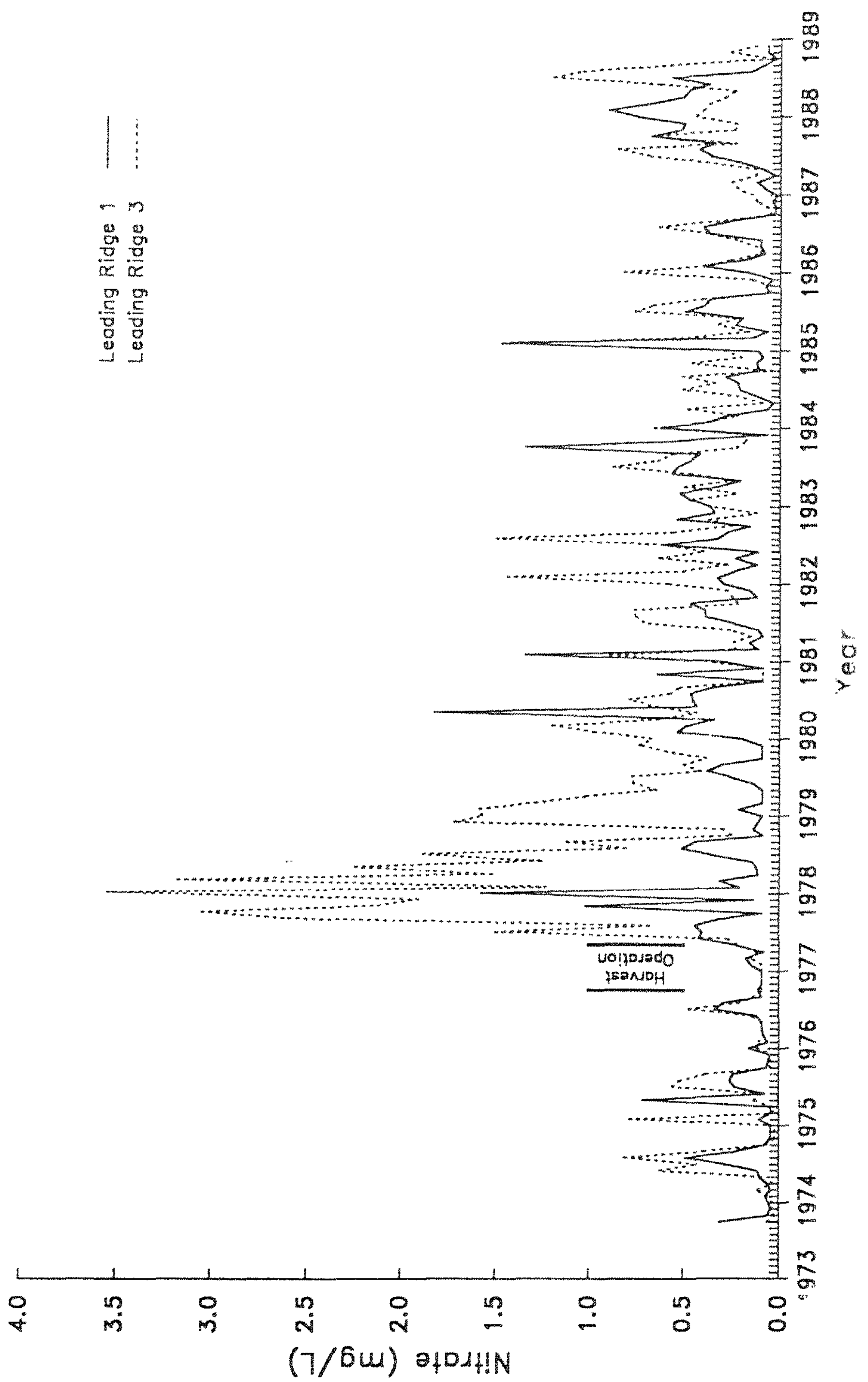

Figure 2. Trends in stream water nitrate concentrations for the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977) and after harvesting.

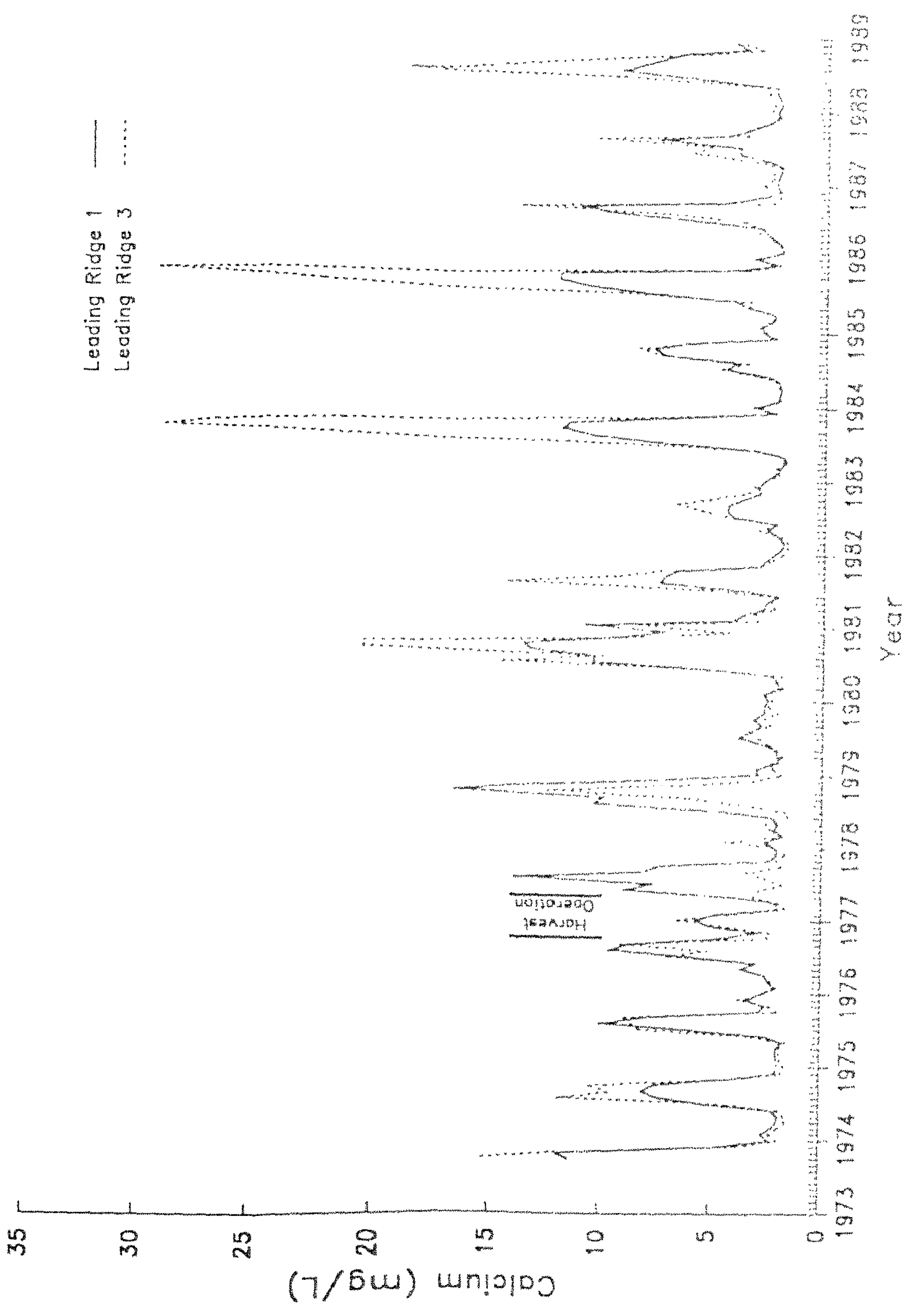

Figure 3. Trends in stream water calcium concentrations for the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977), and after harvesting.

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.

			Post-Harvest Period[1]													
	Pre-Harvest[2]		First Year		Second Year		Third Year		Fifth Year		Seventh Year		Ninth Year		Eleventh Year	
Parameter	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
[1] May 1 through April 30 water year
[2] 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.

			Post-Harvest Period[1]													
	Pre-Harvest[2]		First Year		Second Year		Third Year		Fifth Year		Seventh Year		Ninth Year		Eleventh Year	
Parameter	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
[1] May 1 through October 31
[2] Mean annual export for 1974 through 1976

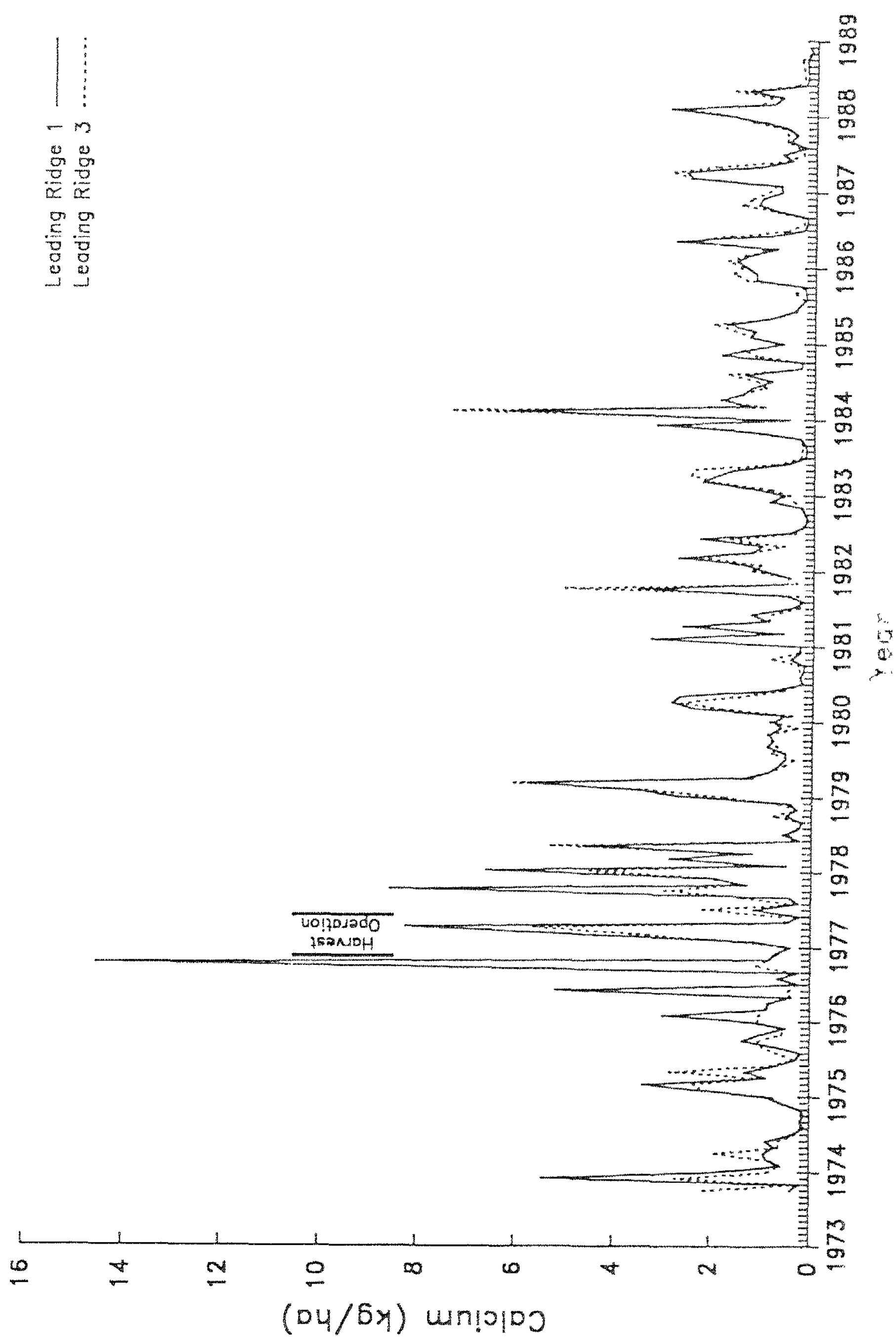

Figure 4. Trends in calcium export from the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977), and after harvesting.

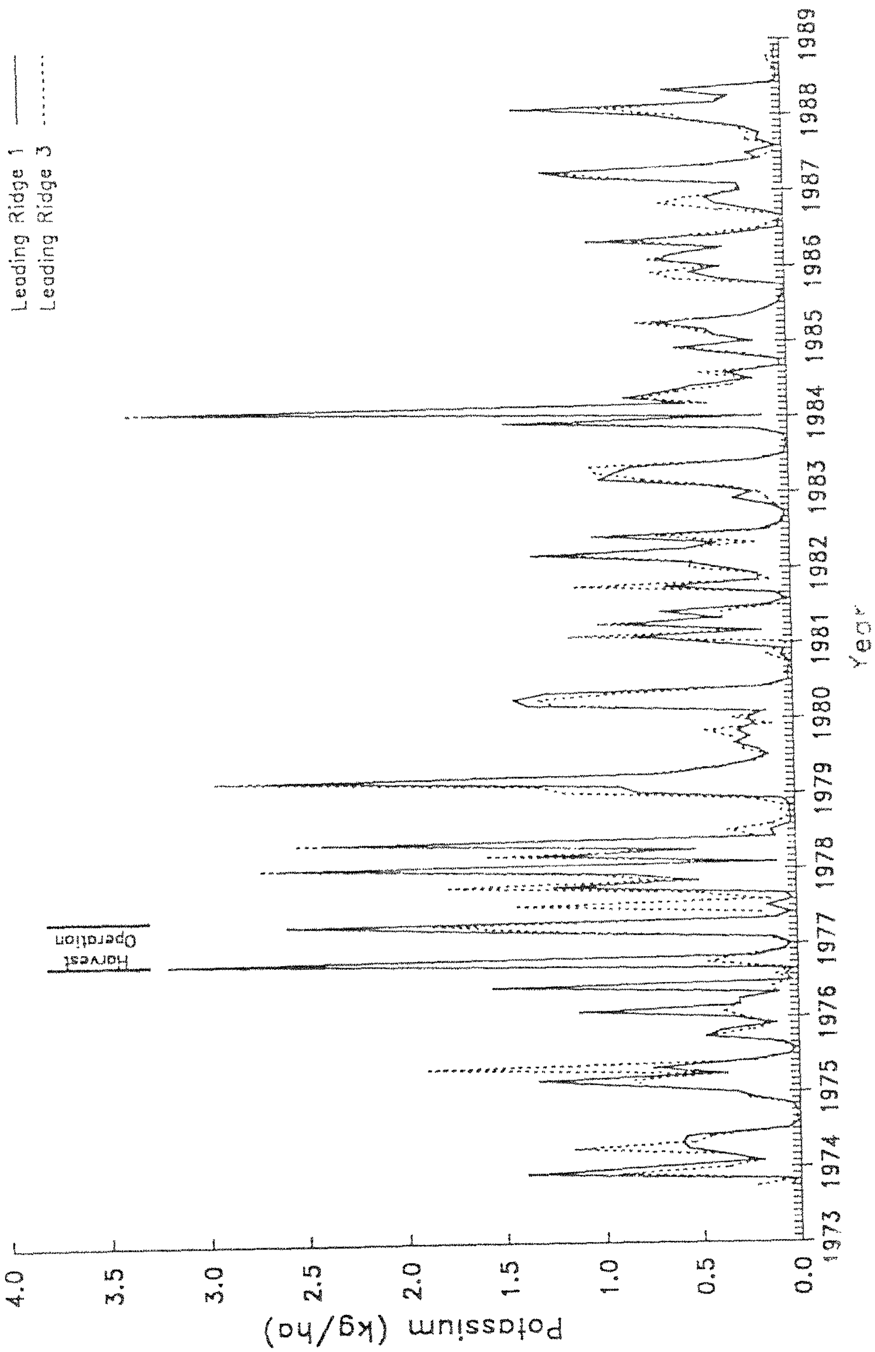

Figure 5. Trends in potassium export from the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977), and after harvesting.

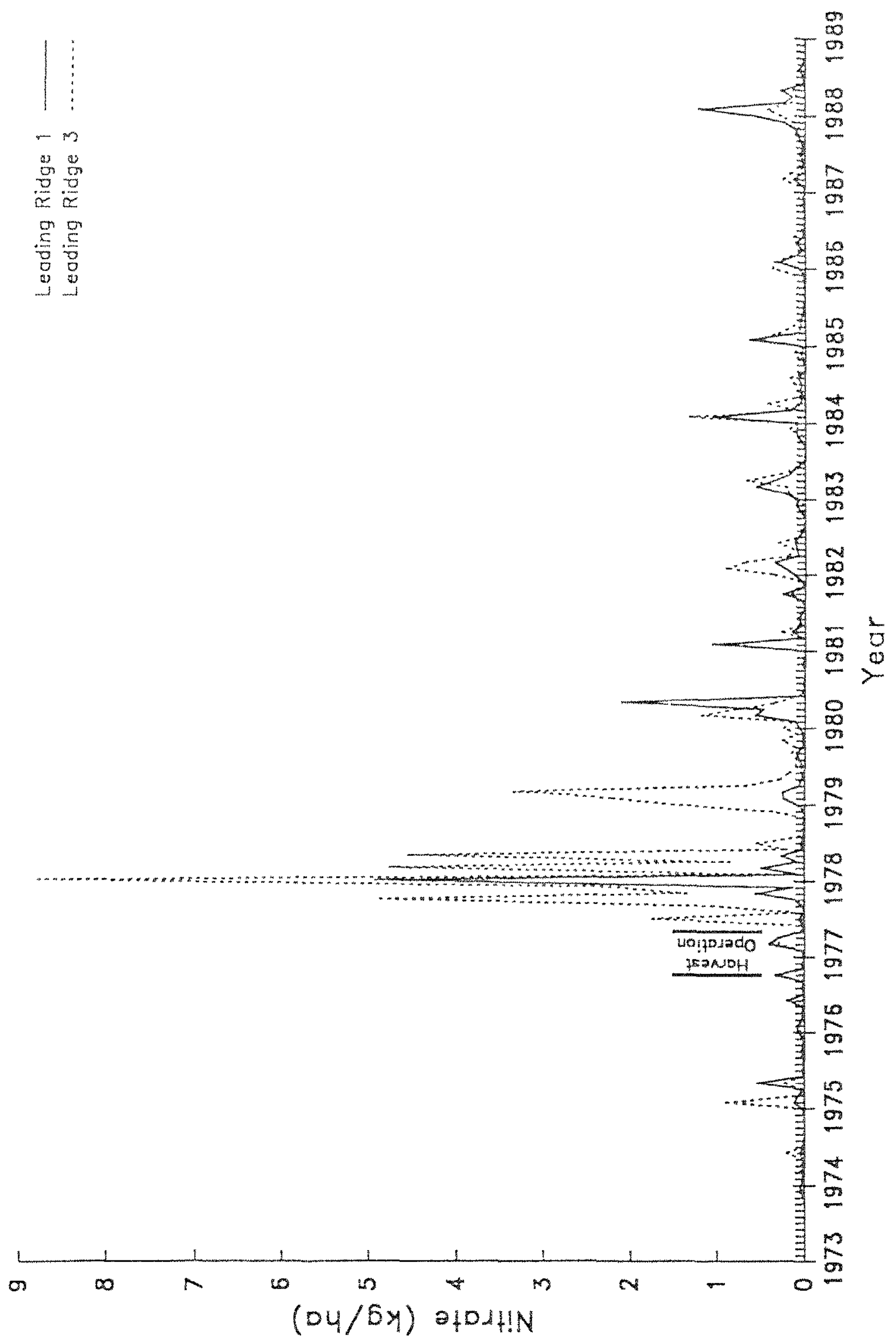

Figure 6. Trends in nitrate export form the control (LR1) and harvested (LR3) watersheds before (1973-1976), during (Oct. 1976-May 1977), and after harvesting.

SUMMARY

The observed changes in stream water chemistry do not represent a signification 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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