The Pennsylvania State University

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EFFECTS OF SOIL AMMONIUM SULFATE APPLICATIONS ON TREE-RING CHEMISTRY IN THREE DIFFUSE-POROUS APPALACHIAN HARDWOOD SPECIES

A Thesis in

Forest Resources

by

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ABSTRACT

The overall objective of this study was to assess the ability of tree-ring chemistry to exhibit chemical differences associated with soil acidification in three Appalachian hardwood tree species. A paired-watershed study was begun in 1989 by the U. S. Forest Service on control (WS7) and treatment (WS3) watersheds at the Fernow Experimental Forest near Parsons, WV, to determine the effects of annual ammonium sulfate applications on soil acidification. Ammonium sulfate was aerially applied to WS3 beginning in 1989 at rates equal to double the ambient levels of atmospheric deposition. Five black cherry, yellow-poplar and red maple trees from each watershed were selected and wood discs at breast height were obtained in 1992 for inorganic chemical analysis using inductively-coupled plasma spectroscopy (ICP). Soil samples were also collected from both watersheds in 1995 and analyzed for plant-available nutrients and metals. Goals of the study were to 1) assess treatment effects on inorganic tree-ring chemistry of the three tree species from treatment WS3 compared to the control WS7, 2) compare methods for expressing tree-ring chemical results (concentrations, molar ratios, and element loads), and 3) document watershed treatment effects on soil chemistry associated with the ammonium sulfate treatment. Results of simple t-tests indicated that significantly greater concentrations of Ca, Mg, K and S in black cherry and yellow-poplar occurred in treatment trees compared to control trees. Some metals such as Zn and B were also found to have significantly greater concentrations in treatment trees, but other metals (Cu, Fe, and Al) were not significantly different. Manganese was significantly lower in treatment black cherry and yellow-poplar trees compared to controls, but no difference was found in red maple. Red maple tree-rings were found to have significantly lower concentrations of P, K, N and S in treatment compared to the control trees, in contrast to the results found for black cherry and yellow-poplar. The timing of the ammonium sulfate treatment was not detectable using tree ring data, most likely due to effects of sapflow and/or translocation. Concentrations were determined to be the best way to analyze data for this study due to the relative measure of element content that concentration results provide, although use of element loads may be suited to nutrient budget studies. Molar ratios of Ca:Al and Ca:Sr for black cherry and yellow-poplar may show some promise for assessing changes in soil chemistry, but more research is needed on ratios. Soil on the treated watershed relative to the control basin showed lower Ca, K, pH, Mn, Cu and Zn and higher Fe after six years of ammonium sulfate treatment. Although results suggested significant response to ammonium sulfate treatment in black cherry and yellow-poplar trees, uncertainty over the comparability of tree-ring chemistry and soils on treated and control watersheds prior to initiation of treatments prevented definite conclusions from being drawn.

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ACKNOWLEDGMENTS

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This work is dedicated to the memory of my father, Martin L. Tepp.

Chapter 1

INTRODUCTION

1.1. Tree-ring Chemistry and Environmental Relationships

The original purpose for analyzing inorganic chemical elements in plant tissue was to identify and quantify the important nutrients plants require to complete their life cycle. In the last 30 years, such analyses have led researchers to speculate about the relationships between the nutrients in a plant and the environment in which the plant grows. An early literature summary of studies dating back to the 1940's was done by Cannon (1960) relating the chemical composition of foliage to the potential for prospecting for ore deposits.

One of the important current applications for tree-ring analysis is to obtain an historical record of the environment of a tree because such data is often lacking. Yanosky and Vroblesky (1992), studying groundwater contamination, concluded yellow-polar trees have the potential for recording changes in environmental quality through study of trace metal concentrations in tree rings. Such relationships are important in light of recent environmental concerns such as global warming, hazardous chemical contamination of soil and water, and atmospheric deposition.

In particular, atmospheric deposition of nitrogen and sulfur compounds in both wet and dry fallout has received considerable attention due to potential negative impacts on forest ecosystems. Analyses of potential ecological indicators such as annual tree rings, soil solutions, and foliar chemistry has led many investigators to suggest atmospheric deposition is a major factor for growth declines of forest species in the eastern United States (Baes and McLaughlin 1984; Bondietti et al. 1989a, 1989b, 1990; Frelich et al. 1989; Ohmann and Grigal 1990). It is proposed that deposition alters the soil chemistry of the forest and reduces availability of essential nutrients to the tree (Bondietti et al. 1989a, 1989b).

1.2. Current Concerns in Tree-ring Chemistry Research

A major concern of tree-ring chemistry research is that the vast majority of studies investigating atmospheric deposition effects on tree-ring chemistry have not been able to develop direct relationships between known soil changes and tree-ring chemistry. Some studies used local sources of pollution, such as smelting operations or proximity to highly industrial areas, as indices of deposition (Guyette and McGinnes 1987; Long and Davis 1989; Dion et al. 1993; Zayed et al. 1992). Other studies relied on known gradients of deposition amounts (Sayre 1987; Bondietti et al. 1989a, 1989b, 1990; Berish and Ragsdale 1985; Ohmann and Grigal 1990). Also, Guyette et al. (1992) constructed mathematical relationships to predict soil pH from Mn concentrations in eastern redcedar tree rings. While these studies have proposed various hypotheses concerning the relationship between atmospheric deposition processes and consequent effects on tree species, the hypotheses are difficult to test due to the lack of information about known soil changes over time and the effects these soil changes have on tree-ring chemistry.

Of studies using known amounts of soil amendments, a few studies have made direct comparisons between known soil inputs and resulting changes to tree-ring or stream-water chemistry. The relation between lime additions and tree-ring chemistry has received some attention (McClenahen et al. 1989; Kashuba-Hockenberry and DeWalle 1994; DeWalle et al. 1995a). The relation between whole-watershed applications of ammonium sulfate and the chemistry of stream-water was studied independently by Kahl et al. (1993) at Bear Brook watershed in Maine and Adams et al. (1993) at the Fernow Experimental Forest in West Virginia. Finally, DeWalle et al. (1995b) presented a summary of results of black cherry tree-ring chemistry data from the Fernow Experimental Forest and the ammonium sulfate applications on WS3 and WS9.

Indirect comparisons of atmospheric inputs to tree-ring chemistry can result in incorrect conclusions concerning deposition effects. Actual deposition may have been more or less than the amounts considered in the studies due to shifting wind patterns or inaccurate reporting of power plant emissions. It is also difficult to determine with certainty if changes in the soil or tree-ring chemistry were due to the cause hypothesized (i.e., regional atmospheric deposition gradients). Direct applications of known quantities of acidic substances over time, in conjunction with chemical analysis of the soil and tree rings, appears to be the next logical step in experimentation. Such acidic applications will help determine if a more accurate cause-and-effect relationship between deposition, soil chemistry, and tree-ring chemistry changes can be ascertained. If such relationships can be determined, tree-ring chemistry has the potential to be used as an indicator of temporal changes in soil fertility provided that interpretation problems of radial translocation and sapflow can also be solved.

The use of tree ring analysis as an indicator of past environment has been hindered due to the potential radial translocation of some elements (Lepp 1975). A partial list of translocated elements include Mn, Ca, Sr, P, K, Ba. and Zn (McClenahen et al. 1989), but movement of elements vary by tree species. Cutter and Guyette (1993) concluded that tree species with low moisture contents and low radial permeability are preferred over other species to reduce the potential for the radial translocation of elements within a tree. Species that have these qualities include many of the conifers and Fagus grandifolia. The process of radial translocation in tree rings introduces additional uncertainty when trying to relate absolute changes in soil chemistry to the chemistry of tree rings.

Vertical translocation (sapflow) is another physiological process which can alter tree-ring chemistry interpretations that has many uncertainties associated with it. Trees are generally categorized as diffuse-porous or ring-porous tree species. Sapflow is considered to occur in a few of the most recent rings in ring-porous species, as opposed to many sapwood rings in diffuse-porous species. Indeed, some tree xylem vessels continue to conduct sap up to several years past the time they were first formed (Kramer and Kozlowski 1979). Difficulty in determining exactly how many rings participate in sapflow, as well as radial translocation, reduces the utility of tree-ring chemistry research when temporal changes are of interest because any detected changes may not have occurred at the time indicated by the tree ring dates.

Another concern is the lack of information about the variability of chemical element concentrations distributed around the tree; only one such study known attempts to address this question (McClenahen et al. 1987). McClenahen and others, after analyzing yellow-poplar increment cores with Proton-Induced X-Ray Emission (PIXE), suggested that sampling more trees rather than taking more than two cores per tree would best reduce variations in the tree-ring chemistry of P, Ca, Al, Mn, and Cu at homogeneous sites. The authors also indicated that anomalistically high concentrations of Na, Ca, Ni and Cu occasionally found in yellow-poplar after using PIXE greatly increased sampling needs. While this study is important for suggesting sampling strategies, it does not specifically address the variation systematically around the whole tree bole and is limited to the species studied (e.g., yellow-poplar).

An additional uncertainty related to tree-ring chemistry is threshold element concentrations for specific tree species. Threshold values for Al have been associated with decreased root growth and reduced nutrient uptake (Kelly et al. 1990; Sucoff et al. 1990; Joslin et al. 1992). If such a threshold is reached, nutrient uptake by the plant may be affected and possibly make interpretation of tree-ring chemistry data more difficult. In addition, Pickens (1995) suggested that there may be an element threshold for Mn in red maple at which uptake of Mn will substantially decrease when the tree has accumulated the threshold amount. This is a concern because changes in the soil environment may have occurred, but the changes may not have been recorded in the tree rings because a particular element threshold has been reached. If such thresholds exist, the elements should be identified and thresholds clearly defined for each tree species.

In addition to physiological concerns in tree-ring chemistry research, it has not been determined what is the "best" way to present data. Data are most often reported in concentration units, but other forms have been proposed. Baes and McLaughlin (1984) used "xylem accumulation rates" using the product of concentration and dry weight of the sample taken from wood cores. This idea has been extended to calculating element loads for the entire tree by using the product of basal area increment and concentration (Jordan et al. 1990). However, calculation of element loads does not entirely negate the negative correlation between concentration and growth rate (DeWalle et al. 1995a).

Molar ratios of element concentrations have also been used in an attempt to more easily identify trends over time (Bondietti et al. 1989a). Recently, Ca/Al ratios obtained from soil and foliage were suggested as viable ecological indicators (Cronan and Grigal 1995). However, the authors did not consider the use of Ca/Al ratios from wood samples to be a reliable indicator, citing problems with radial translocation of elements, tree to tree variability in element concentrations, and calculated Ca/Al molar ratios that are very large and thus susceptible to minor changes in Al concentrations producing large changes in the Ca/Al ratio.

1.3. Objectives and Hypotheses

The overall objective of this study was to assess the ability of tree-ring chemistry to detect chemical differences associated with soil acidification in three Appalachian hardwood tree species. The study was conducted using a paired watershed approach, with a control watershed (WS7) and a treatment watershed (WS3) located on the Fernow Experimental Forest near Parsons, WV. The treated watershed had received ammonium sulfate fertilization at rates double the ambient atmospheric loads since January 1989. Secondary objectives were to evaluate different ways of expressing tree-ring data and document the soil chemistry associated with the ammonium sulfate treatment. The following hypotheses were tested:

Hypothesis 1. Significant differences in element concentrations will be found in the tree-ring chemistry of red maple, black cherry and yellow-poplar trees obtained from control and treatment watersheds after three years of ammonium sulfate treatment.

Hypothesis 2. Element concentrations, rather than loads or molar ratios, are the most appropriate tree ring chemistry results to detect soil differences.

Hypothesis 3. The time at which the ammonium sulfate treatment was initiated can be detected using the timing of differences in tree-ring chemistry concentrations from all three diffuse-porous tree species obtained from control and treatment watersheds.

Hypothesis 4. Significant chemical differences have occurred in the plant-available soil chemistry on treatment WS3 compared to the control WS7 after six years of ammonium sulfate treatment.

Chapter 2

DESCRIPTION OF STUDY AREA

This study was conducted on a control watershed (WS7) and treatment watershed (WS3) located on the Fernow Experimental Forest near Parsons, West Virginia (39° 3' 15" N, 79° 41' 15" W). The majority of soils on the Fernow were mapped as Calvin silt loam (loamy-skeletal, mixed, mesic Typic Dystrochrept) derived from sandstone and shale of the Hampshire formation (Adams et al. 1995). Depth to bedrock is generally less than one meter.

Average climatic data for the area provided from the climate station in Elkins, WV, about 24 km southeast of Parsons, showed an average annual air temperature of 9.8°C for the years 1941-1970 (National Climatic Data Center 1980). WS3 precipitation averaged 1471 mm and had an average annual streamflow of 666 mm, while WS7 had average precipitation of 1418 mm and annual streamflow of 882 mm for the years 1957-1990 (Adams et al. 1994). Measured evaporation was about 45% of total precipitation from 1957-1990.

The treated (WS3) and control (WS7) watersheds for this experiment were very similar with respect to elevation, species composition and precipitation (Table 2.1). WS7 had 30% fewer trees per hectare compared to WS3 but only 16% less basal area, indicating some possible growth differences between the two watersheds. In addition, there was a relatively large-scale herbicide treatment applied to WS7 for several years in an earlier treatment (Table 2.2). WS3 also had herbicide applied in conjunction with patch cuttings, but only a small fraction of the total watershed area was treated. In addition, WS3 herbicide applications occurred during one season only as opposed to the multiple-year applications on WS7. It appears that less competition occurred among tree species on WS7 than on WS3.

Beginning in January 1989, granular ammonium sulfate [$(NH_4)_2SO_4$] was applied on WS3 via helicopter which added approximately twice the ambient load of N and S deposition from the atmosphere each year. Amounts applied in 1989 were 34 kg ha^{-1} in January and November and 101 kg ha^{-1} in July. During 1990 to 1992, 34 kg ha^{-1} was applied in March and November and 101 kg ha^{-1} was applied in July. More information concerning the treatment applications can be found in Adams et al. (1993).

Table 2.1. Characteristics of two experimental watersheds on the Fernow Experimental Forest, West Virginia.

Characteristic	WS3	WS7
Area (ha)	34.3	24.2
Aspect	S	ENE
Min. elevation (m)	735	725
Max. elevation (m)	860	855
Stand age (yr)	24	24
Stand density (trees ha^{-1})	537.5	376.8
Basal area (m^2 ha^{-1})	3.87	3.27
Dominant tree species	*Prunus serotina* *Acer rubrum* *Betula lenta* *Fagus grandifolia*	*Prunus serotina* *Acer rubrum* *Betula lenta* *Acer saccharum*

Source: Adams et al. (1995)

Table 2.2. Comparison of treatments and land use history for two experimental watersheds on Fernow Experimental Forest, WV.

Watershed	Treatments	Dates
WS3	Weir installation	5/51
	Intensive selection cut	10/58 - 2/59
	Repeated cut	9/63 - 10/63
	Patch cuttings w/ herbicide	7/68 - 8/68
	Clearcut, left stream buffer	7/69 - 5/70
	Cut buffer, clear channel	11/72
	Begin ammonium sulfate treatment	1/89
WS7	Weir installation	11/56
	Upper 12.1 ha clearcut	11/63 - 3/64
	Herbicide upper cut	5/64 - 10/69
	Lower 12.1 ha clearcut	10/66 - 3/67
	Herbicide lower cut	5/67 - 10/69

Source: Adams et al. (1994)

Chapter 3

MATERIALS AND METHODS

3.1. Wood Sampling

3.1.1. Collection and Preparation

Three tree species were selected for this study due to their common occurrence on both watersheds; black cherry (Prunus serotina Ehrh.), red maple (Acer rubrum L.), and yellow-poplar (Liriodendron tulipifera L.). In 1992, personnel from the Northeastern Forest Experiment Station in Parsons, WV, cut 3-cm-thick wood disks at breast height (1.4 m) with a chain saw from felled trees and measured DBH (diameter at breast height, 1.4 m) with a DBH tape to the nearest 0.1 inch. Five control and five treatment trees for each species were obtained from the respective watersheds, WS7 and WS3. Disks were kept frozen until delivered to Penn State University where they were transferred to large, labeled zip-lock freezer bags and kept in a freezer when not being used.

Each disk was sanded on one face using a belt sander with a medium-grit sanding belt to aid in identification of annual rings. The disks were then cut into quadrants using a band saw based on the presence of areas with rings growing close together (Figure 3.1a), referred to as compression

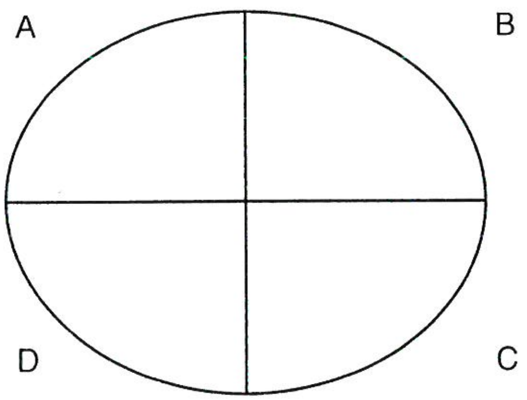

Figure 3.1a. Saw cuts used to separate a wood disc into quadrants for sampling. Letters indicate the relative positions of the quadrants: A = C = normal wood, B = compression wood, D = tension wood.

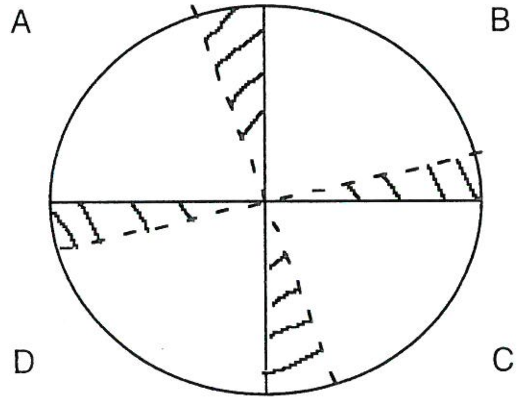

Figure 3.1b. Locations of wood wedges (cross-hatched areas) cut from disc quadrants used for sampling. Letters indicate the relative positions of the quadrants: A = C = normal wood, B = compression wood, D = tension wood.

wood for this discussion. If such an area was present through visual inspection, then the disk was cut to include the tension wood in a separate quadrant. If no tension wood was apparent the disk was randomly cut into quadrants. Quadrant codes were assigned based on their relation to each other (Figure 3.1a). Quadrants "A" and "C" were located to the left and right, respectively, of the compression wood quadrant "B" (if present), while quadrant "D" was opposite the compression wood (Figure 3.1a). Each quadrant was placed in a zip-lock freezer bag labeled with the designated tree number and quadrant code. Wood wedges were cut from the same relative end of each quadrant using the band saw (Figure 3.1b). These strips were then separated into sample periods under a 30x magnification stereoscope using a stainless steel utility knife on a Plexiglas surface. Sample periods were:

Treatment Period	1989-1992
Pre-Treatment I	1986-1988
Pre-Treatment II	1981-1985
Pre-Treatment III	1976-1980

Red maple and yellow-poplar samples included all four sample periods, while black cherry could only be analyzed through the Pre-Treatment II period due to insufficient amounts of wood in the Pre-treatment III period. In addition, the year at which the heartwood-sapwood boundary occurred in black cherry and yellow-polar was recorded. Heartwood-sapwood boundaries were not determined for red maple due to abnormal discoloration of the wood discs near the pith, possibly due to disease. The total length of growth rings in each sample was measured three times using a digital micrometer to the nearest 0.01 mm and measurements averaged to obtain an average growth length used for computation of basal area increment and element loadings.

Sanded edges were removed from the samples with a stainless steel chisel to prevent possible contamination of wood samples by the sandpaper. Samples were rinsed with deionized water several times during processing and sterile, unpowdered rubber gloves were worn whenever wood was handled. Quadrant samples were combined for yellow-poplar and red maple before being submitted for analysis due to budget constraints (n=1 for each period per tree), but black cherry quadrants were analyzed separately (n=4 for each period per tree) and later combined for statistical analysis.

3.1.2. Chemical Analysis

All wood samples were submitted to Agricultural Analytical Services Laboratory at Penn State University for inorganic chemical analysis. Inductively-coupled plasma emission spectroscopy (ICP) was used to determine concentrations of P, K, Ca, Mg, Mn, Fe, Cu, B, Al, Zn, Na, and Sr (Dahlquist and Knoll 1978). Total nitrogen was determined using the Dumas Method (Campbell 1991), while total sulfur was analyzed using the ICP method described by Huang and Schulte (1985) (Appendix, Tables A.2, A.3, A.5, A.6, A.8, A.9).

Due to the low sulfur content of the samples, a lower detection curve was developed by laboratory personnel. Black cherry samples originally analyzed by the standard, higher curve were re-analyzed using the low curve. Since three of the 360 black cherry samples did not have enough wood remaining to undergo this additional analysis, a regression equation was fit (adj. $R^2 = 0.823$) to predict the low curve result from the standard curve numbers obtained previously. The predicted results for these three black cherry samples were used for all statistical analyses.

Replicate samples from three previously analyzed black cherry samples were included with each subsequent submission of samples to check data consistency (Table 3.1). An examination of the percent coefficients of variation (%CV = [standard deviation/mean] x 100) from these replicates showed that Al, Fe, and Na had high variation, but the remaining elements generally had %CV's < 10%. In the cases of Al and Fe, high CV's were due to the low mean concentrations of these elements in the tree rings which caused small changes in concentration to produce a large %CV. High variation in Na was due to a few very high detected values.

3.1.3. Basal Area Increment Calculation

Average sample length was calculated from the three length measurements made for each sample cut from the wood wedges. Bark thickness was measured with a ruler on quadrants A and D to the nearest 0.16 cm (1/16 inch) then averaged to obtain an estimated bark thickness

Table 3.1. Coefficients of variation (%) for replicate samples of black cherry tree rings submitted to the Penn State Plant Analysis Laboratory.

Element	Rep 1	Rep 2	Rep 3	Average of All Reps
	n=3	n=3	n=3	
P	6.18	13.07	0.00	6.42
K	2.70	3.60	1.77	2.69
Ca	2.63	4.11	2.60	3.11
Mg	0.00	3.99	0.00	1.33
Mn	5.16	4.63	12.97	7.58
Fe	19.22	16.90	17.35	17.83
Cu	9.97	11.05	5.44	8.82
B	4.17	5.20	3.85	4.41
Al	43.29	28.31	40.80	37.47
Zn	11.14	11.44	7.02	9.87
Na	50.46	20.36	55.65	42.16
Sr	0.00	4.47	2.92	2.46
N	10.73	8.95	4.02	7.90
S	4.77	6.07	8.21	6.35

for each tree. Wood diameter at breast height (DBH_w) was calculated as:

$$DBH_w = DBH - 2B$$

where DBH is the field-measured diameter at breast height in inches and B is average bark thickness in inches. Total wood radius is then:

$$R_w = 0.5(2.54 \cdot DBH_w)$$

where R_w is the wood radius in centimeters and DBH_w is wood diameter at breast height in inches.

Basal area increment for sample n in each quadrant (BAI_n) was then calculated as

$$\Delta BAI = BA_n - BA_{n-1} = \frac{\pi(r_n{}^2 - r_{n-1}{}^2)}{4}$$

where BA_n is the outer quadrant basal area, BA_{n-1} is the inner quadrant basal area, and r is the wood radius for the outer and inner samples. Wood located closest to the pith was designated n=1 and n increased for each more recent sample period. Since tree quadrants were kept frozen while not being used, it is assumed very little wood shrinkage occurred. The load of an element was then defined as the sample concentration of the element multiplied by the BAI for that sample to give the milligrams of element times square centimeter of BAI per kilogram of wood.

3.1.4. Statistical Analyses

All statistical calculations were performed using Minitab 8.21 (Minitab Inc., 1991) on a Macintosh Classic computer. Simple t-tests (ONEWAY) were used for all element concentration comparisons, element loads, and element molar ratios. T-tests were also used to compare BAI's and sample lengths between control and treatment trees, within each species and sampling period.

3.2. Soil Samples

Soil samples were collected in May 1995 from WS3 and WS7 to assess the effect of the ammonium sulfate treatment on the soil chemical environment. Soil pits were located within 2 m of fifty previously-located plot centers for a leaf litter study (Adams, personal communication). Locations of these plot centers on WS3 and WS7 are given in Figures 3.2 and 3.3, respectively. Soil samples were taken from these fifty locations because the exact locations where sample trees were obtained from in 1992 could not be determined.

One soil pit was dug near each plot center using a "Sharpshooter" shovel on WS3 and a post-hole digger on WS7 for a total of twenty-five pits on each watershed. At each pit, separate soil samples from the A and B mineral horizons were obtained with a garden trowel. Depth of each horizon was also measured using a ruler to the nearest centimeter. Rubber gloves were worn throughout the process. Samples were kept in a freezer until submitted for chemical analysis.

Soil samples were submitted to Agricultural Analytical Services at Pennsylvania State University for available P, K, Ca, and Mg using the Mehlich 3 method (Wolf and Beegle, 1991), available metals (Mn, Fe, Cu, Zn, Na, Al, Pb, Ni, Cd) using the Diagnostic Soil Test Method (ASTM D5435-93) and pH using the water method (Eckert and Sims, 1991). Results obtained from the laboratory (Appendix, Tables A.10 to A.12) were analyzed using simple t-tests (ONEWAY). Samples were analyzed by comparing horizons for WS3 and WS7.

3.3. Assumptions and Limitations

The basic assumption of this study was that the control WS7 and treatment WS3 were essentially the same except for the ammonium sulfate treatment because there is a lack of pre-treatment soil and tree-ring chemistry data from the watersheds. Pre-treatment soils data do not exist for the control WS7 while the limited pre-treatment soils data available for treatment WS3 are not comparable to the data I collected in 1995 because different chemical analysis techniques were used. No pre-treatment tree-ring chemistry data existed at all.

A logical statistical comparison would have been to do time-series analysis on the tree-ring chemistry data to assess trends over time. Due to the young age of the trees and the 3-5 year time increments needed to obtain an adequate mass of wood for ICP analysis, too few observations over time were available for time-series analysis.

Due to budget constraints, only five trees from each watershed were utilized for this study. This small sample size necessitates caution when comparing the results to other studies. The methods used to analyze the available soil elements may not be the best for forested areas, but they are well-known methods that should be readily reproducible. Despite these limitations, it is hoped the data presented here will be used as an early treatment data set for future tree-ring chemistry studies on these watersheds.

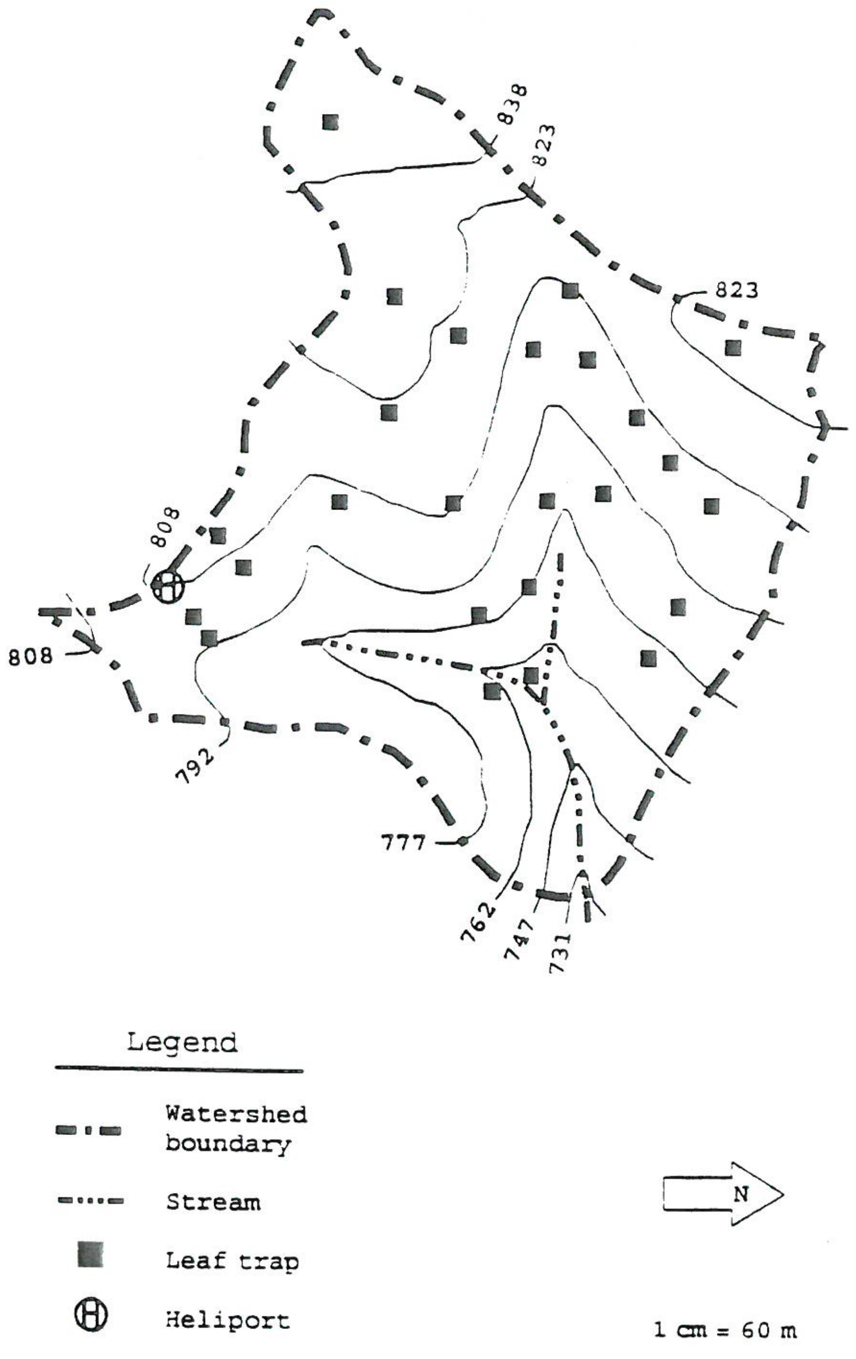

Figure 3.2. Locations of soil sampling points for control watershed WS7 on Fernow Experimental Forest. Soil samples were collected from points marked by leaf traps (Source: Adams, 1995).

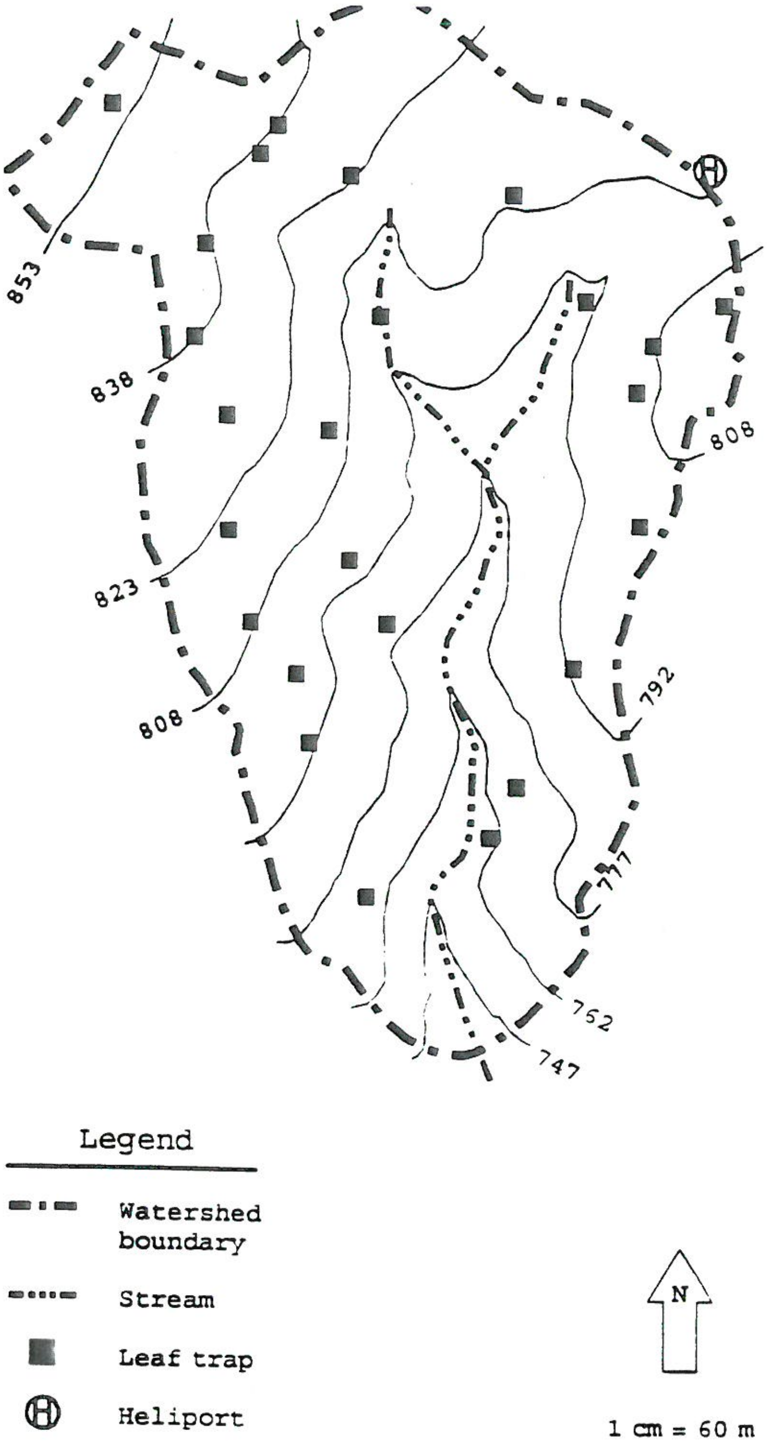

Figure 3.3. Locations of soil sampling points for treatment watershed WS3 on Fernow Experimental Forest. Soils samples were collected from points marked by leaf traps (Source: Adams, 1995).

Chapter 4

RESULTS

4.1. Wood Samples

4.1.1. Concentration Results

4.1.1.1. Black Cherry

Examination of the black cherry results for all quadrants combined reveals that 50% of the elements tested were significantly different ($\alpha <$ 0.05) between WS3 and WS7 for the Treatment period, 1989-1992 (Table 4.1). Of these, P, K, Ca, B, Sr, and S had higher mean concentrations in the treatment trees compared to control trees, while Mn was lower in the treatment trees. Although N had a higher mean concentration in treatment trees, the difference was not significant. The Pre-treatment I period had 86% of elements significantly different between control and treatment trees. Significantly higher concentrations of P, K, Ca, B, Sr, S, Mg, Zn occurred in treatment trees while Mn, Fe, Cu, and Al concentrations were lower. Pre-treatment II had 43% of elements with significant differences and one element moderately different ($\alpha < 0.10$) from control trees. Lower concentrations in treatment trees were found for Mn, Cu, Na and S while Mg and Sr concentrations were higher. Graphical

Table 4.1. Black cherry tree-ring chemistry (mg kg^{-1}) for control (WS7) and treatment (WS3) watersheds by time periods.

		Treatment Period (1989-1992)		Pre-treatment I (1986-1988)		Pre-treatment II (1981-1985)	
Elmt	Stat	WS7	WS3	WS7	WS3	WS7	WS3
		n=20	n=20	n=20	n=20	n=20	n=20
P	M	122.00	146.00**	50.50	66.00**	20.00	29.50
	s	24.62	28.36	16.69	6.81	28.84	11.46
K	M	1015.00	1213.00**	356.00	421.50**	225.00	234.00
	s	147.30	297.60	72.94	79.29	270.40	77.90
Ca	M	431.50	502.00**	331.50	504.00**	171.00	320.00**
	s	87.38	64.20	92.35	60.12	50.58	103.69
Mg	M	103.00	113.00	65.00	98.00**	27.50	57.00**
	s	33.73	31.64	23.95	31.56	22.03	29.22
Mn	M	76.30	22.45**	66.40	22.55**	28.95	13.95**
	s	20.08	4.39	29.78	5.20	10.05	5.52
Fe	M	10.95	10.90	8.10	5.25**	6.20	8.40
	s	7.84	14.01	4.89	1.52	2.24	17.85
Cu	M	1.88	1.78	1.50	1.29**	1.77	0.98**
	s	0.40	0.32	0.24	0.15	0.70	0.13
B	M	3.46	3.74**	2.72	2.98**	2.63	2.73
	s	0.48	0.34	0.22	0.28	0.19	0.25
Al	M	8.60	1.70	2.90	1.30**	1.10	1.10
	s	22.66	1.22	2.99	0.47	0.31	0.31
Zn	M	2.66	5.70	1.72	3.49**	2.49	2.06
	s	0.74	10.23	0.59	3.14	1.63	1.89
Na	M	11.15	10.00	9.85	8.30	7.35	5.85**
	s	3.59	3.21	4.45	3.10	2.66	1.27
Sr	M	3.91	5.23**	3.47	5.36**	2.79	4.09**
	s	0.48	0.63	0.54	0.64	0.51	0.67
N	M	1273.00	1321.00	897.00	950.00	743.00	722.00
	s	212.60	250.40	101.70	175.90	106.00	129.40
S	M	82.35	90.40**	60.00	64.44**	61.80	53.95*
	s	8.87	14.49	5.00	6.18	18.20	3.87

M = mean. s = standard deviation.

* indicates significant difference at $\alpha < 0.10$ between control WS7 and treatment WS3 within each time period, ** at $\alpha < 0.05$.

representations of Ca, S, and B data for all three periods are shown in Figures 4.1, 4.2, and 4.3, respectively, to give the reader a visual sense of the concentration results over time.

4.1.1.2. Red Maple

In contrast to black cherry, red maple showed relatively few significant differences between control and treatment trees (Table 4.2). A moderately significant difference ($\alpha < 0.10$) was indicated for Mg during the Treatment period, showing a lower mean concentration in treatment trees compared to control trees. Significant differences ($\alpha < 0.05$) occurred for P, K, and N in treatment trees, all of which had lower concentrations than trees from the control watershed. Pre-treatment I samples exhibited moderate differences ($\alpha < 0.10$) for K, Ca, and Fe. Concentrations for K and Ca were lower in treatment trees, but Fe was greater. Significant differences ($\alpha < 0.05$) were found for P and S in treatment trees, both of which had lower concentrations compared to control trees. Pre-treatment II samples showed similar results for P and S. Only S was significantly lower in Pre-treatment III treatment samples. Graphical representations of Ca and S data for all periods are shown in Figures 4.4 and 4.5, respectively.

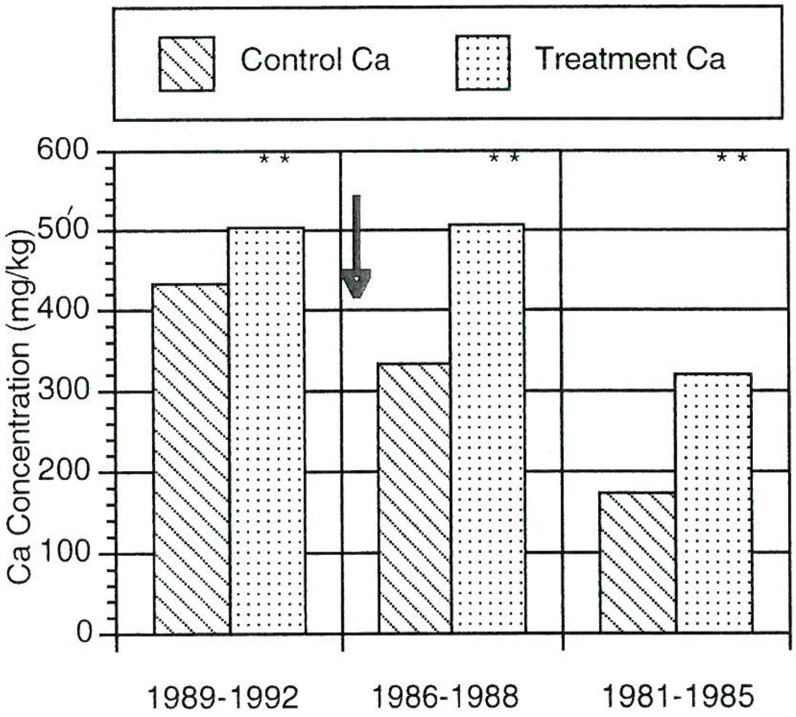

Figure 4.1. Calcium tree-ring concentrations from black cherry trees by time period for control (WS7) and treatment (WS3) watersheds. The arrow indicates initiation of ammonium sulfate treatment. Two stars indicate significant differences at $\alpha < 0.05$ between control WS7 and treatment WS3 within each time period.

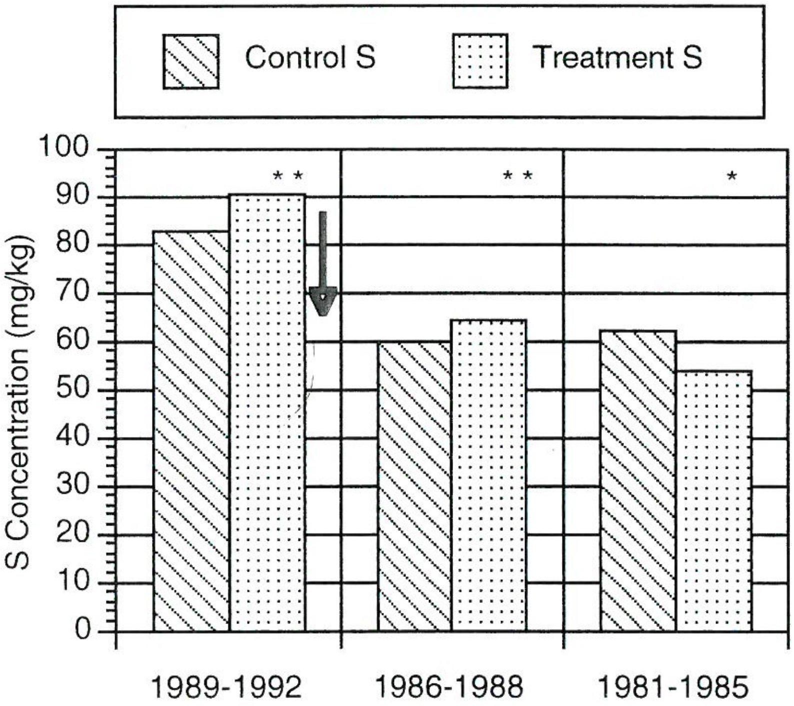

Figure 4.2. Sulfur tree-ring concentrations from black cherry trees by time period for control (WS7) and treatment (WS3) watersheds. The arrow indicates initiation of ammonium sulfate treatment. Two stars indicate significant differences at $\alpha < 0.05$ between control WS7 and treatment WS3 within each time period, while one star is significant at $\alpha < 0.10$.

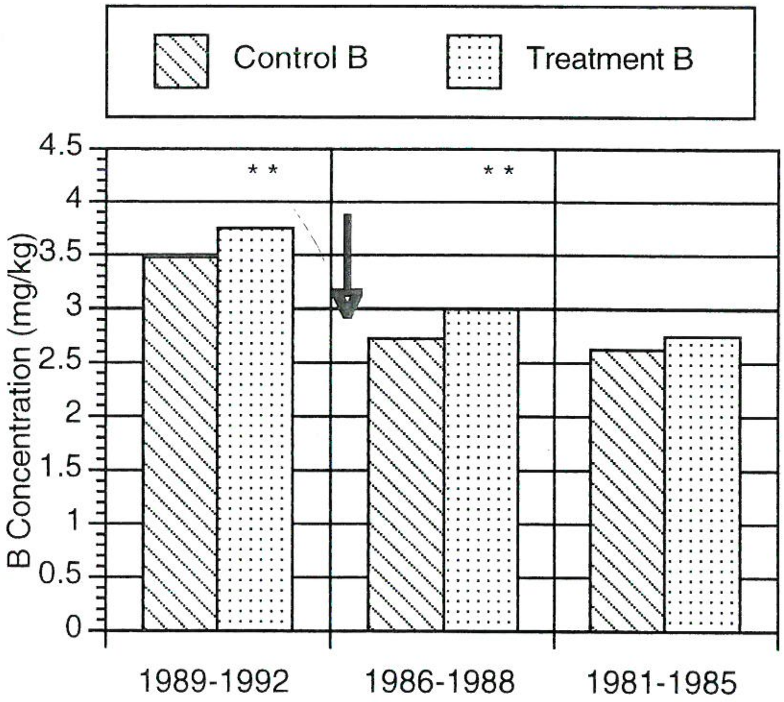

Figure 4.3. Boron tree-ring concentrations from black cherry trees by time period for control (WS7) and treatment (WS3) watersheds. The arrow indicates initiation of ammonium sulfate treatment. Two stars indicate significant differences at $\alpha < 0.05$ between control WS7 and treatment WS3 within each time period.

Table 4.2. Red maple tree-ring chemistry (mg kg^{-1}) for control (WS7) and treatment (WS3) watersheds by time periods.

		Treatment Period (1989-1992)		Pre-treatment I (1986-1988)		Pre-treatment II (1981-1985)		Pre-treatment III (1976-1980)	
Elmt	Stat	WS7	WS3	WS7	WS3	WS7	WS3	WS7	WS3
		n=5	n=5	n=5	n=5	n=5	n=5	n=4	n=5
P	M	148.00	102.00**	82.00	70.00**	82.00	66.00**	80.00	56.00*
	s	10.95	4.47	8.37	7.07	8.37	8.94	24.50	5.48
K	M	1526.00	1048.00**	622.00	542.00*	722.00	498.00	1437.50	478.00
	s	291.90	111.40	62.61	46.58	315.63	46.58	1239.50	45.50
Ca	M	612.00	586.00	666.00	622.00*	682.00	658.00	747.50	1030.00
	s	46.58	20.74	32.09	35.64	35.64	55.41	116.70	711.40
Mg	M	82.00	70.00*	82.00	72.00	98.00	92.00	110.00	100.00
	s	10.95	7.07	8.37	13.04	25.88	17.89	33.67	20.00
Mn	M	161.40	169.20	174.40	180.40	173.20	190.00	176.50	255.20
	s	51.39	37.55	45.26	36.37	37.50	38.96	45.91	106.94
Fe	M	6.20	7.60	4.60	7.20*	4.20	7.00	3.75	6.20
	s	1.30	4.34	1.52	2.17	1.30	7.31	1.71	2.39
Cu	M	1.66	1.40	1.06	1.12	0.86	1.10	0.85	0.94
	s	0.36	0.17	0.23	0.38	0.11	0.32	0.13	0.17
B	M	3.00	2.82	2.56	2.48	2.52	2.46	2.63	2.56
	s	0.32	0.19	0.11	0.15	0.15	0.09	0.28	0.13
Al	M	1.00	1.20	1.00	1.00	1.00	1.00	1.00	1.00
	s	0.00	0.4472	0.00	0.00	0.00	0.00	0.00	0.00
Zn	M	7.08	9.14	6.92	5.76	6.60	5.32	7.75	6.36
	s	2.36	7.16	2.39	2.26	2.36	2.28	2.22	3.63
Na	M	15.80	10.60*	13.20	8.80	8.00	11.20	9.00	6.80
	s	5.26	1.52	10.06	1.64	2.35	4.21	2.45	1.30
Sr	M	3.42	3.40	3.74	3.54	3.66	3.62	3.93	5.02
	s	0.42	0.51	0.42	0.51	0.38	0.53	0.85	2.50
N	M	1376.00	1192.00**	934.00	826.00	746.00	696.00	722.50	662.00
	s	104.10	110.30	136.30	114.40	69.86	66.93	83.42	96.80
S	M	122.20	101.40*	74.80	64.80**	69.00	57.80**	71.75	59.00**
	s	20.39	13.26	5.81	4.66	2.45	5.36	4.27	7.65

M = mean. s = standard deviation.

* indicates significance at α < 0.10 between control WS7 and treatment WS3 within each time period, ** at α < 0.05.

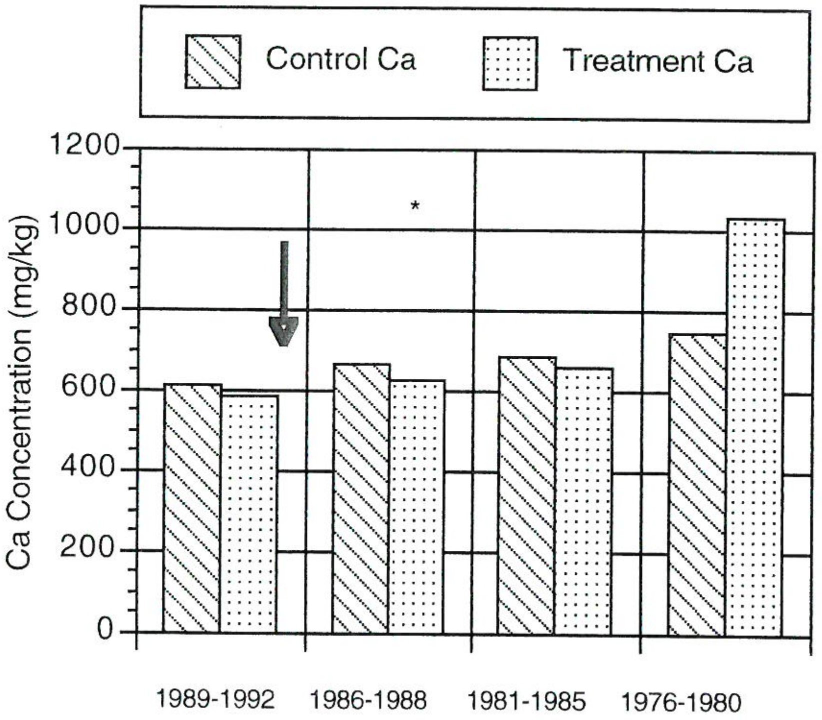

Figure 4.4. Calcium tree-ring concentration data from red maple trees by time period for control (WS7) and treatment (WS3) watersheds. The arrow indicates initiation of ammonium sulfate treatment. One star indicates significant differences at $\alpha < 0.10$ between control WS7 and treatment WS3 within each time period.

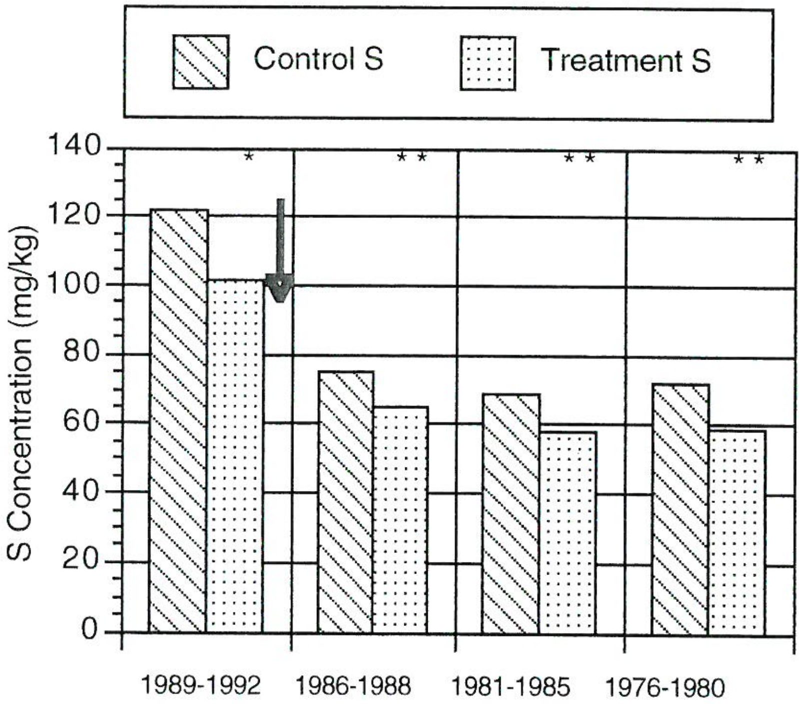

Figure 4.5. Sulfur tree-ring concentration data from red maple trees by time period for control (WS7) and treatment (WS3) watersheds. The arrow indicates initiation of ammonium sulfate treatment. Two stars indicate significant differences at $\alpha < 0.05$ between control WS7 and treatment WS3 within each time period, while one star is significant at $\alpha < 0.10$.

4.1.1.3. Yellow-poplar

Treatment period comparisons for yellow-poplar showed moderately significant differences ($\alpha < 0.10$) for K and N (Table 4.3), treatment mean concentrations being higher than the control mean. Other significant differences ($\alpha < 0.05$) included higher concentrations of Ca, Mg, B, Sr, and S when compared to control trees. Manganese had a significantly lower concentration in treatment trees during this period.

Pre-treatment I results were similar to the treatment period. Significantly higher concentrations ($\alpha < 0.05$) of Ca, Fe, B, and Sr were found in trees from the treated watershed while Mn was lower. Moderately significant differences ($\alpha < 0.10$) occurred for Mg, Na, and N in treatment trees, all of which showed higher concentrations than control trees.

Pre-treatment II comparisons continued the previous trend. Calcium, Fe, B, and S were significantly ($\alpha < 0.05$) higher in treatment trees, while Mn and Cu were lower. Treatment trees contained a moderately significant ($\alpha < 0.10$) difference for K, with K being lower in treated trees rather than control trees.

The oldest ring samples from Pre-treatment III had significantly lower concentrations of K, Mn, and Cu in treatment trees compared to trees from the control watershed. Again, Sr concentrations in trees from the treatment watershed were significantly higher than controls during this

Table 4.3. Yellow-poplar tree-ring chemistry (mg kg^{-1}) for control (WS7) and treatment (WS3) watersheds by time periods.

		Treatment Per. (1989-1992)		Pre-treatment I (1986-1988)		Pre-treatment II (1981-1985)		Pre-treatment III (1976-1980)	
Elmt	Stat	WS7	WS3	WS7	WS3	WS7	WS3	WS7	WS3
		n=5	n=5	n=5	n=5	n=5	n=5	n=5	n=4
P	M	86.00	171.00	58.00	60.00	36.00	34.00	10.00	15.00
	s	16.73	101.64	25.88	33.17	8.94	18.17	0.00	10.00
K	M	1072.00	1712.00*	628.00	684.00	652.00	402.00*	546.00	247.00**
	s	144.10	541.40	97.30	316.90	155.90	189.00	194.00	118.40
Ca	M	670.00	1006.00**	714.00	994.00**	710.00	956.00**	858.00	927.00
	s	144.00	123.60	110.10	97.60	76.80	90.70	135.90	118.40
Mg	M	94.00	158.00**	120.00	132.00*	122.00	146.00*	126.00	127.50
	s	11.40	22.80	7.07	10.95	8.37	23.02	16.73	9.57
Mn	M	92.80	17.40**	106.40	18.00**	90.80	16.60**	91.60	14.50**
	s	35.32	4.51	46.10	5.34	41.14	5.77	42.06	4.43
Fe	M	10.80	11.60	3.60	6.80**	3.20	6.20**	6.20	5.50
	s	13.54	5.08	1.52	1.10	0.45	2.05	2.39	1.29
Cu	M	1.92	1.92	1.20	1.50	1.54	1.22**	2.30	1.25**
	s	0.11	0.40	0.10	0.42	0.15	0.19	0.77	0.06
B	M	1.98	2.56**	1.92	2.22**	1.90	2.16**	2.06	2.13
	s	0.15	0.21	0.08	0.08	0.10	0.09	0.18	0.15
Al	M	6.00	8.00	5.00	6.60	6.80	6.60	9.80	7.75
	s	1.00	2.74	0.71	2.07	0.84	1.95	1.92	1.71
Zn	M	4.24	7.38	3.74	8.34	6.46	3.08	3.98	9.40
	s	1.27	4.35	0.61	7.52	5.22	1.22	1.78	10.71
Na	M	8.80	18.00	6.60	12.00*	6.40	8.00	10.20	8.00
	s	1.79	12.67	1.34	4.85	0.55	2.45	3.96	2.83
Sr	M	4.62	8.42**	4.82	8.22**	4.86	7.96**	5.60	7.60**
	s	0.93	0.98	0.73	0.84	0.58	0.72	0.53	0.86
N	M	1262.00	1788.00*	1202.00	1256.00	1004.00	1108.00	1084.00	1028.00
	s	85.80	500.00	383.00	173.90	87.90	124.60	141.00	103.40
S	M	87.00	137.00**	76.80	97.20*	73.60	86.40	75.80	84.25
	s	5.57	34.12	9.93	18.27	4.62	16.50	11.86	7.14

M = mean. s = standard deviation.

* indicates significance at $\alpha < 0.10$ between control WS7 and treatment WS3 within each time period, ** at $\alpha < 0.05$.

period. Graphical representations of Ca, S, and B data for yellow-poplar are shown in Figures 4.6, 4.7, and 4.8, respectively.

4.1.2. Molar Element Ratios

Analysis of molar ratios yielded many significant ($\alpha < 0.05$) differences between control and treatment black cherry trees (Table 4.4). Significant differences were detected for all ratios analyzed during all sample periods, with the exception of the Ca:Sr ratio during Pre-treatment I (1986-1988). In contrast, red maple ratios indicated only one significant comparison; a moderate difference ($\alpha < 0.10$) for Ca:Al during the Pre-treatment I sample period (Table 4.5). Yellow-poplar showed more variety in ratio results than the other two species (Table 4.6). Moderate differences ($\alpha < 0.10$) were found for Ca:Al during the Pre-treatment II and III sample periods, as well as Mg:Al during Pre-treatment II. Many significant differences still occurred, though, with Ca:Mn, Mg:Mn, Ca:Sr, and Sr:Mn showing significant differences between control and treatment trees during all four sample periods. Graphs of Ca:Al molar ratios are given in Figures 4.9, 4.10, and 4.11 for black cherry, red maple, and yellow-poplar, respectively.

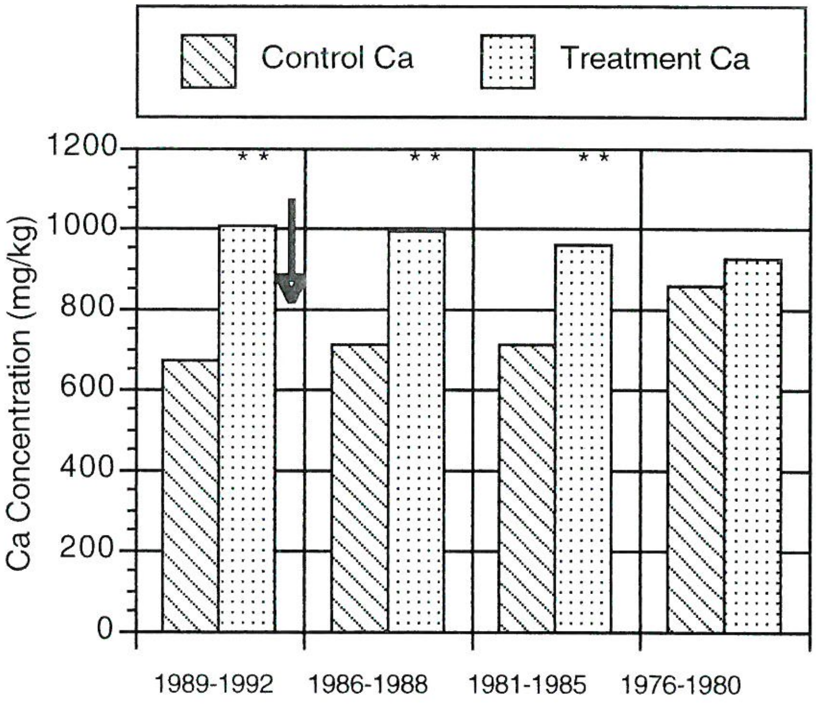

Figure 4.6. Calcium tree-ring concentrations from yellow-poplar trees by time period for control (WS7) and treatment (WS3) watersheds. The arrow indicates initiation of ammonium sulfate treatment. Two stars indicate significant differences at $\alpha < 0.05$ between control WS7 and treatment WS3 within each time period.

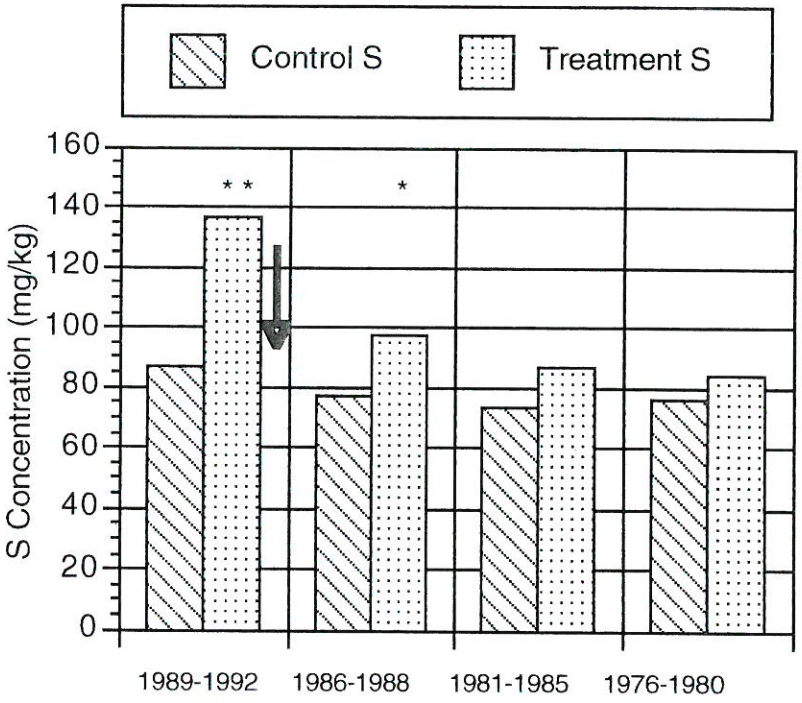

Figure 4.7. Sulfur tree-ring concentrations from yellow-poplar trees by time period for control (WS7) and treatment (WS3) watersheds. The arrow indicates initiation of ammonium sulfate treatment. Two stars indicate significant differences at $\alpha < 0.05$ between control WS7 and treatment WS3 within each time period, while one star is significant at $\alpha < 0.10$.

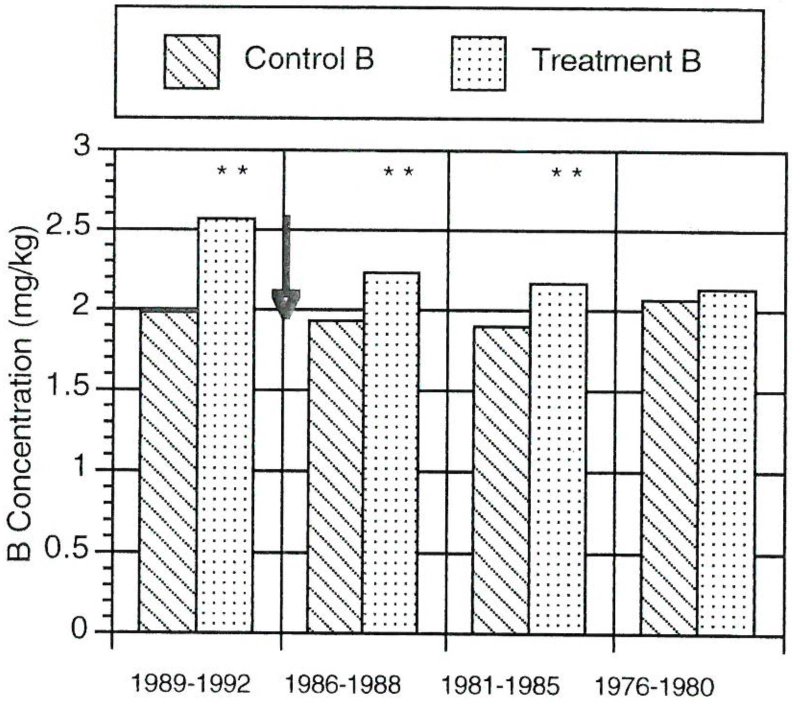

Figure 4.8. Boron tree-ring concentrations from yellow-poplar trees by time period for control (WS7) and treatment (WS3) watersheds. The arrow indicates initiation of ammonium sulfate treatment. Two stars indicate significant differences at $\alpha < 0.05$ between control WS7 and treatment WS3 within each time period.

Table 4.4. Black cherry tree-ring element molar ratios (kg:kg) for control (WS7) and treatment (WS3) watersheds by time periods.

		Treatment Period (1989-1992)		Pre-treatment I (1986-1988)		Pre-treatment II (1981-1985)	
Elmt	Stat	WS7	WS3	WS7	WS3	WS7	WS3
		n=20	n=20	n=20	n=20	n=20	n=20
Ca/Al	M	126.84	259.68**	125.82	287.84**	108.91	204.18**
	s	81.26	109.86	85.62	86.12	38.51	76.91
Ca/Mn	M	8.02	31.66**	7.50	31.89**	8.84	32.41**
	s	1.74	7.06	1.77	7.54	3.78	6.43
Mg/Al	M	49.66	98.61**	40.69	95.00**	28.61	60.28**
	s	32.92	48.12	30.14	46.09	24.93	33.69
Mg/Mn	M	3.07	11.58**	2.44	9.98**	2.32	8.97**
	s	0.60	3.51	0.89	2.93	2.23	2.17
Ca/Sr	M	241.20	210.21**	205.20	205.66	132.66	166.92**
	s	36.22	15.14	36.20	13.81	16.86	32.70
Sr/Mn	M	0.034	0.152**	0.039	0.157**	0.067	0.202**
	s	0.009	0.041	0.016	0.042	0.026	0.056

M = mean. s = standard deviation.

* indicates significance at $\alpha < 0.10$ between control WS7 and treatment WS3 within each time period, ** at $\alpha < 0.05$.

Table 4.5. Red maple tree-ring element molar ratios (kg:kg) for control (WS7) and treatment (WS3) watersheds by time periods.

		Treatment Per. (1989-1992)		Pre-treatment I (1986-1988)		Pre-treatment II (1981-1985)		Pre-treatment III (1976-1980)	
Ratio	Stat	WS7	WS3	WS7	WS3	WS7	WS3	WS7	WS3
		n=5	n=5	n=5	n=5	n=5	n=5	n=4	n=5
Ca/Al	M	412.07	353.49	448.43	418.80*	459.20	443.04	503.30	693.50
	s	31.37	83.49	21.61	24.00	24.00	37.31	78.60	479.00
Ca/Mn	M	5.60	4.92	5.52	4.87	5.64	4.90	6.19	5.33
	s	1.64	1.02	1.42	1.03	1.44	1.08	2.06	1.60
Mg/Al	M	91.11	71.11	91.11	80.00	108.89	102.22	122.22	111.11
	s	12.17	21.66	9.30	14.49	28.76	19.88	37.41	22.22
Mg/Mn	M	1.30	0.97	1.14	0.94	1.35	1.13	1.54	0.96
	s	0.58	0.23	0.40	0.27	0.50	0.28	0.70	0.28
Ca/Sr	M	394.42	381.32	392.88	388.11	410.36	400.42	420.46	427.14
	s	44.50	40.92	46.24	38.30	45.31	32.63	41.24	67.32
Sr/Mn	M	0.015	0.013	0.015	0.013	0.014	0.012	0.015	0.012
	s	0.006	0.002	0.006	0.002	0.005	0.003	0.006	0.003

M = mean. s = standard deviation.

* indicates significance at $\alpha < 0.10$ between control WS7 and treatment WS3 within each time period, ** at $\alpha < 0.05$.

Table 4.6. Yellow-poplar tree-ring element molar ratios (kg:kg) for control (WS7) and treatment (WS3) watersheds by time periods.

		Treatment Per. (1989-1992)		Pre-treatment I (1986-1998)		Pre-treatment II (1981-1985)		Pre-treatment III (1976-1980)	
Ratio	Stat	WS7	WS3	WS7	WS3	WS7	WS3	WS7	WS3
		n=5	n=5	n=5	n=5	n=5	n=5	n=5	n=4
Ca/Al	M	75.19	99.99	96.69	112.31	71.10	106.01*	60.01	83.81*
	s	8.74	60.52	12.13	47.21	10.92	38.06	11.09	21.43
Ca/Mn	M	11.79	83.78**	11.66	80.00**	14.53	85.89**	18.28	97.5**
	s	7.14	23.74	7.85	19.19	11.52	26.93	15.73	44.08
Mg/Al	M	17.56	24.76	27.11	24.41	20.17	25.89*	14.76	19.02
	s	1.55	11.54	4.28	9.17	2.85	6.27	3.69	4.97
Mg/Mn	M	2.60	21.86**	3.07	17.45**	3.81	20.94**	3.85	21.73**
	s	1.09	7.51	1.57	3.83	2.25	4.18	2.141	8.24
Ca/Sr	M	316.58	262.31**	323.79	264.78**	320.15	262.42**	333.85	266.42**
	s	19.19	29.75	16.74	16.64	23.79	8.65	32.00	9.81
Sr/Mn	M	11.79	83.78**	11.66	80.00**	14.53	85.89**	18.28	97.5**
	s	7.14	23.74	7.85	19.19	11.52	26.93	15.73	44.08

M = mean. s = standard deviation.

* indicates significance at $\alpha < 0.10$ between control WS7 and treatment WS3 within each time period, ** at $\alpha < 0.05$.

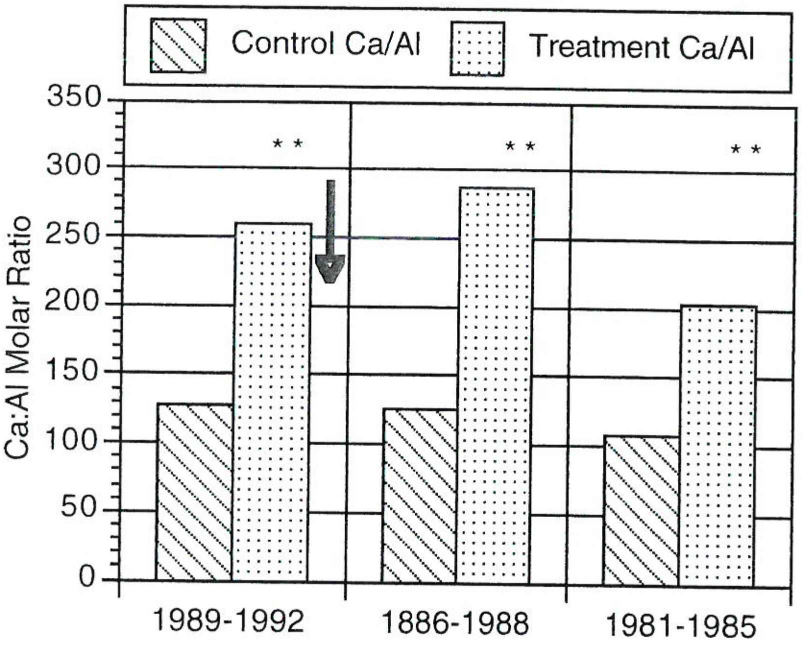

Figure 4.9. Ca:Al tree-ring element molar ratios from black cherry trees by time period for control (WS7) and treatment (WS3) watersheds. The arrow indicates initiation of ammonium sulfate treatment. Two stars indicate significant differences at $\alpha < 0.05$ between control WS7 and treatment WS3 within each time period.

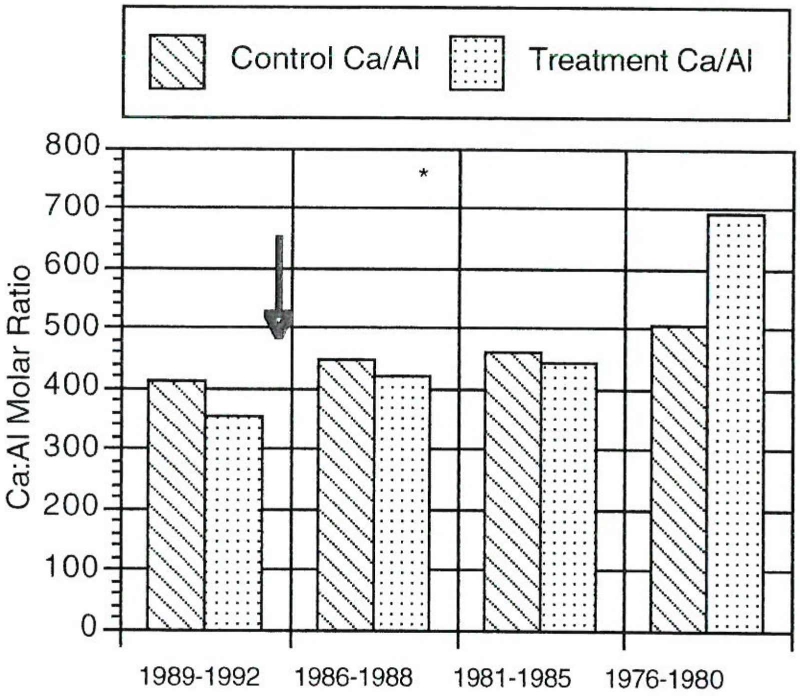

Figure 4.10. Ca:Al tree-ring element molar ratios from red maple trees by time period for control (WS7) and treatment (WS3) watersheds. The arrow indicates initiation of ammonium sulfate treatment. One star indicates significant differences at $\alpha < 0.10$ between control WS7 and treatment WS3 within each time period.

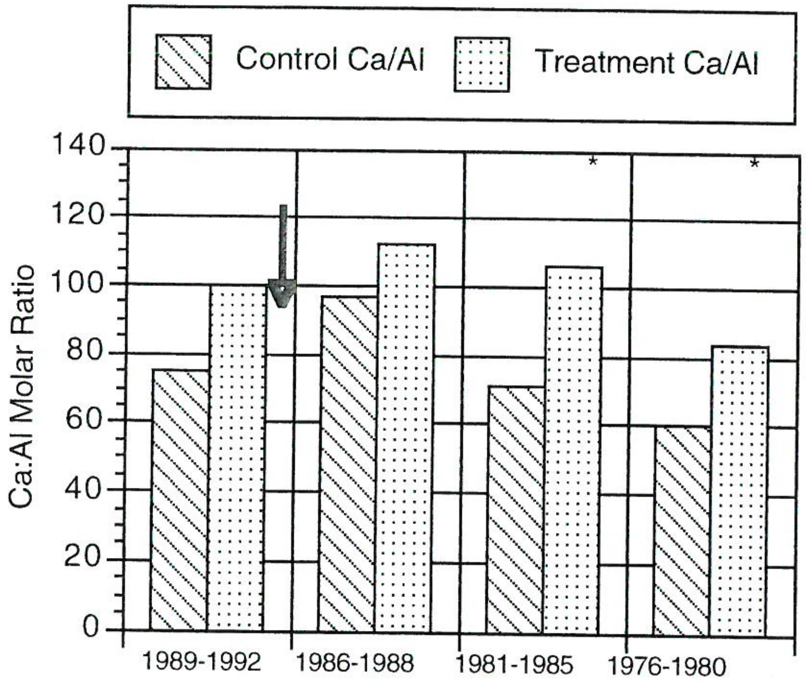

Figure 4.11. Ca:Al tree-ring element molar ratios from yellow-poplar trees by time period for control (WS7) and treatment (WS3) watersheds. The arrow indicates initiation of ammonium sulfate treatment. One star indicates significant differences at $\alpha < 0.10$ between control WS7 and treatment WS3 within each time period.

4.1.3. BAI x Concentration Loads

4.1.3.1. Black Cherry

Basal area increments calculated for each quadrant of black cherry samples were multiplied by the element concentrations of those quadrants and then combined and analyzed for differences (Table 4.7). Twelve of the 14 elements were significantly different for the Treatment period (1989-1992). Aluminum and zinc were the only elements that were not significantly different. Pre-treatment I showed a moderately significant difference between the control and treatment Mg means, while Zn was not statistically different. All other elements were significantly different. Pre-treatment II samples showed Ca, Mg, Mn, Cu, Na, Sr, N and S with significant ($\alpha < 0.05$) differences and B was moderately different ($\alpha < 0.10$).

Sample lengths and BAI's were significantly different during all three sample periods with control trees having higher values than treatment trees in the Treatment and Pre-treatment I periods. This difference is related to the observation that in the Treatment and Pre-treatment I periods control trees had higher BAI x concentration values than those from the treatment watershed. Pre-treatment II had lower sample lengths and BAI in treatment trees, but in some cases the BAI x concentration loads were higher in treatment trees due to higher concentrations.

Table 4.7. Black cherry tree ring BAI x concentration loads (mg cm^2 kg^{-1}) for control (WS7) and treatment (WS3) watersheds by time periods. Also included are sample lengths (LEN, mm) and basal area increments (BAI, cm^2) for all quadrants combined.

		Treatment Period (1989-1992)		Pre-treatment I (1986-1988)		Pre-treatment II (1981-1985)	
Elmt	Stat	WS7	WS3	WS7	WS3	WS7	WS3
		n=20	n=20	n=20	n=20	n=20	n=20
P	M	2654.50	1224.50**	778.03	478.56**	370.69	474.37
	s	1070.30	432.20	337.81	143.74	431.07	149.59
K	M	22086.00	10061**	5438.20	2991.20**	4168.80	3802.30
	s	7089.00	3432.00	1826.20	820.40	3950.30	1031.30
Ca	M	9199.00	4293.00**	5075.90	3650.40**	3307.40	5196.40**
	s	2812.00	1618.00	1920.00	1126.70	979.20	1460.80
Mg	M	2156.90	937.20**	974.80	718.50*	497.90	905.90**
	s	693.50	441.60	459.60	310.80	316.60	385.70
Mn	M	1643.90	201.70**	1007.00	163.60**	556.41	224.51**
	s	623.40	108.90	485.60	59.30	200.26	70.57
Fe	M	229.15	90.82**	121.03	38.57**	119.47	153.71
	s	189.94	96.90	66.20	18.00	42.56	362.55
Cu	M	40.94	15.18**	23.29	9.42**	35.16	16.34**
	s	17.01	5.96	8.43	3.17	23.57	3.81
B	M	74.34	33.13**	41.81	21.62**	52.97	45.31*
	s	21.60	15.91	13.02	6.18	17.82	6.96
Al	M	213.93	15.36	42.79	9.75**	21.28	18.61
	s	669.93	12.24	39.63	5.18	5.60	7.47
Zn	M	56.86	50.57	26.28	24.62	48.02	34.84
	s	22.61	96.54	10.63	22.90	28.93	33.52
Na	M	235.28	81.91**	149.14	58.15**	143.35	96.17**
	s	87.95	36.42	82.88	23.00	57.19	19.30
Sr	M	85.13	45.10**	53.78	39.11**	55.03	67.33**
	s	27.62	17.83	17.98	12.90	16.60	11.35
N	M	26872	11121**	13763	6715**	14769	11996**
	s	8120	3991	4570	1743	4420	2698
S	M	1783.80	779.10**	918.40	474.80**	1215.70	900.00**
	s	553.00	305.20	288.80	140.90	395.10	163.30

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Table 4.7 (continued)

		Treatment Period (1989-1992)		Pre-treatment I (1986-1988)		Pre-treatment II (1981-1985)	
Elmt	Stat	WS7	WS3	WS7	WS3	WS7	WS3
		n=20	n=20	n=20	n=20	n=20	n=20
LEN	M	16.85	7.19**	14.74	6.52**	29.02	17.89**
	s	4.17	3.52	3.88	2.33	6.66	3.74
BAI	M	21.76	9.02**	15.41	7.39**	20.17	16.67**
	s	6.22	4.51	4.82	2.47	6.38	2.54

M = mean. s = standard deviation.

* indicates significance at $\alpha < 0.10$ between control WS7 and treatment WS3 within each time period, ** at $\alpha < 0.05$.

4.1.3.2. Red Maple

Pre-treatment III was the only period that showed significant differences between control and treatment values for the red maple BAI x concentration analysis (Table 4.8). Phosphorus, Mg, B, Al, Na, N, and S were all significantly ($\alpha < 0.05$) lower in treatment trees compared to controls while K, Cu, and Zn were moderately ($\alpha < 0.10$) lower than control trees.

In addition to the BAI x concentration differences, comparisons of BAI calculations also yielded some differences (Table 4.8). Control trees were found to have a moderately ($\alpha < 0.10$) greater mean BAI compared to treatment trees during Treatment and Pre-treatment II sample periods, as well as moderately ($\alpha < 0.10$) greater length during Pre-treatment II. Also, control trees showed significantly ($\alpha < 0.05$) greater length and BAI growth compared to treatment trees during Pre-treatment III.

4.1.3.3. Yellow-poplar

Results of the BAI x concentration analysis for yellow-poplar during the Treatment Period showed ten elements with significant differences ($\alpha < 0.05$) between control and treatment trees (Ca, Mg, Mn, Cu, B, Al, Zn, Na, N, S) (Table 4.9). Similar to the other species studied, control trees had higher BAI x concentration values than treatment trees. Phosphorus was moderately different ($\alpha < 0.10$) during this period. BAI was also found to be significantly ($\alpha < 0.05$) greater for control trees.

Table 4.8. Red maple tree ring BAI x concentration loads (mg cm^2 kg^{-1}) for control (WS7) and treatment (WS3) watersheds by time periods. Also included are sample lengths (LEN, mm) and basal area increments (BAI, cm^2) for all quadrants combined.

		Treatment Per. (1989-1992)		Pre-treatment I (1986-1988)		Pre-treatment II (1981-1985)		Pre-treatment III (1976-1980)	
Elmt	Stat	WS7	WS3	WS7	WS3	WS7	WS3	WS7	WS3
		n=5	n=5	n=5	n=5	n=5	n=5	n=4	n=5
P@	M	64.57	32.26	29.46	21.88	59.50	41.26	40.35	17.49**
	s	38.62	13.82	10.72	9.54	17.94	19.00	16.93	3.86
K@	M	676.57	334.68	223.44	167.27	574.97	308.16	712.40	150.33*
	s	390.40	144.44	83.06	68.79	436.28	128.15	582.33	36.95
Ca@	M	258.56	183.16	237.85	187.40	499.73	392.11	371.87	289.66
	s	143.14	74.93	86.33	59.90	168.81	102.89	93.20	116.01
Mg@	M	36.47	22.76	29.36	22.88	72.63	57.78	55.12	30.33**
	s	22.55	10.94	10.45	11.71	30.66	27.61	20.28	3.99
Mn@	M	63.25	51.34	29.38	53.46	121.53	113.42	86.69	75.60
	s	29.69	22.70	16.61	17.28	30.39	35.39	22.60	20.46
Fe	M	262.60	251.10	160.03	225.34	304.00	367.00	194.80	196.30
	s	127.40	219.50	65.54	117.13	118.50	293.60	121.00	92.90
Cu	M	70.22	42.63	38.44	31.82	61.66	64.22	41.95	29.44*
	s	35.40	16.27	17.36	7.96	17.22	17.19	8.29	8.91
B	M	124.15	87.59	90.63	75.42	183.07	148.81	130.92	79.29**
	s	60.18	35.91	29.29	26.64	56.17	47.56	32.92	14.04
Al	M	42.61	33.83	35.61	30.46	72.94	60.48	49.41	31.06**
	s	22.93	9.97	12.24	10.74	23.07	19.10	7.83	5.59
Zn	M	266.04	227.28	234.89	163.11	463.00	339.70	392.10	197.90*
	s	79.44	89.34	71.19	60.07	159.30	255.00	171.30	121.30
Na	M	763.50	326.10	559.20	264.30	587.70	663.40	446.98	210.44**
	s	697.00	136.10	645.70	107.20	248.80	251.50	138.96	53.86
Sr	M	140.94	102.30	132.48	104.15	267.24	211.72	193.54	145.82
	s	67.35	36.09	43.40	27.27	88.91	38.83	46.30	38.47
N@	M	580.57	367.81	326.56	247.14	551.84	411.61	355.98	202.62**
	s	292.78	150.64	92.51	85.45	206.10	92.45	58.84	30.55
S@	M	50.75	30.97	26.20	19.61	50.03	35.25	35.69	18.09**
	s	23.36	12.11	7.23	7.03	14.61	13.40	7.99	2.74

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Table 4.8 (continued)

		Treatment Per. (1989-1992)		Pre-treatment I (1986-1988)		Pre-treatment II (1981-1985)		Pre-treatment III (1976-1980)	
Elmt	Stat	WS7	WS3	WS7	WS3	WS7	WS3	WS7	WS3
		n=5	n=5	n=5	n=5	n=5	n=5	n=4	n=5
LEN	M	8.55	7.00	8.40	7.66	23.06	19.56*	28.77	16.24**
	s	3.48	2.72	2.95	2.52	7.17	5.44	4.69	4.27
BAI	M	10.65	7.91*	8.90	7.61	18.24	15.12*	13.42	7.77**
	s	5.58	3.53	3.56	2.76	6.05	4.73	3.26	1.85

M = mean. s = standard deviation.

@' Means and standard deviations for these elements are actual values divided by 100.

* indicates significance at $\alpha < 0.10$ between control WS7 and treatment WS3 within each time period, ** at $\alpha < 0.05$.

Table 4.9. Yellow-poplar tree ring BAI x concentration loads (mg cm^2 kg^{-1}) for control (WS7) and treatment (WS3) watersheds by time periods. Also included are sample lengths (LEN, mm) and basal area increments (BAI, cm^2) for all quadrants combined.

		Treatment Per. (1989-1992)		Pre-treatment I (1986-1988)		Pre-treatment II (1981-1985)		Pre-treatment III (1976-1980)	
Elmt	Stat	WS7	WS3	WS7	WS3	WS7	WS3	WS7	WS3
		n=5	n=5	n=5	n=5	n=5	n=5	n=5	n=4
P@	M	55.03	33.84*	35.98	13.67**	35.92	17.22**	4.21	9.02
	s	15.37	17.93	19.41	3.38	13.17	8.89	1.27	6.05
K@	M	678.28	408.50	383.05	163.96**	670.49	211.52**	227.00	149.62
	s	112.88	322.01	99.11	46.45	292.58	114.46	105.95	73.06
Ca@	M	433.36	226.16**	433.01	313.18	719.85	575.73	351.22	560.51**
	s	138.00	142.08	101.27	205.62	229.29	256.33	91.80	112.06
Mg@	M	60.93	33.53**	72.47	41.11**	122.24	89.43	53.36	76.42*
	s	18.57	16.74	10.47	26.18	30.16	41.77	18.56	6.21
Mn@	M	59.97	3.69**	62.03	5.57**	87.06	10.22**	40.26	8.66**
	s	28.96	1.84	22.74	3.26	41.65	5.96	26.10	2.55
Fe	M	708.30	207.10	213.40	211.30	324.20	359.10	273.40	328.40
	s	903.50	28.40	81.50	154.10	104.70	202.40	165.90	69.70
Cu	M	122.31	39.41**	72.06	43.77*	153.76	71.48**	90.27	75.04
	s	21.66	18.37	8.16	27.44	40.72	32.23	22.81	6.56
B	M	126.40	54.02**	115.95	69.52*	192.16	126.77*	85.40	127.92**
	s	22.84	25.25	16.34	48.51	54.44	52.98	23.50	16.78
Al	M	390.99	149.86**	300.80	227.80	687.10	407.60*	396.07	460.97
	s	129.65	46.08	54.50	218.40	195.40	219.90	95.03	74.85
Zn	M	266.93	123.96**	224.10	309.50	678.60	165.50	153.80	569.30
	s	79.97	22.78	38.60	335.30	685.70	82.70	47.20	654.20
Na	M	550.42	302.68**	394.81	304.06	633.50	429.00*	426.20	484.20
	s	71.16	86.84	75.27	112.42	127.80	156.90	214.20	185.50
Sr	M	297.42	188.67	292.40	264.80	497.10	481.80	231.69	458.48**
	s	84.88	112.54	68.10	184.40	168.20	214.40	62.63	82.77
N@	M	806.89	356.86**	731.20	385.83*	1011.22	648.10*	446.58	616.65**
	s	152.60	152.88	283.18	271.15	290.31	274.90	122.42	75.03
S@	M	55.65	27.20**	46.52	28.52*	73.79	48.20*	30.76	50.75**
	s	10.88	10.70	10.01	18.25	19.14	18.25	6.74	7.58

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Table 4.9 (continued)

		Treatment Per. (1989-1992)		Pre-treatment I (1986-1988)		Pre-treatment II (1981-1985)		Pre-treatment III (1976-1980)	
Elmt	Stat	WS7	WS3	WS7	WS3	WS7	WS3	WS7	WS3
		n=5	n=5	n=5	n=5	n=5	n=5	n=5	n=4
LEN	M	11.69	5.11**	12.82	9.07**	30.06	22.87**	27.33	29.58
	s	2.49	2.67	1.41	5.77	7.63	7.62	5.00	5.73
BAI	M	16.02	6.13**	15.06	9.33**	25.09	17.67**	10.52	15.76**
	s	3.64	3.35	1.94	4.98	5.99	2.56	3.23	1.90

M = mean. s = standard deviation.

@ Means and standard deviations for these elements are actual values divided by 100.

* indicates significance at $\alpha < 0.10$ between control WS7 and treatment WS3 within each time period, ** at $\alpha < 0.05$.

Pre-treatment I had significant differences for P, K, Mg, and Mn, and moderately significant ($\alpha < 0.10$) differences for Cu, B, N, and S. Again, control values were greater than treatment values, including BAI. A similar trend is found during the Pre-treatment II sample period.

Unlike previous sample periods for yellow-poplar and the other species studied, Pre-treatment III showed higher BAI x concentration values for treatment trees compared to control trees. Significantly higher values were found for Ca, Mn, B, Sr, N, and S in treatment trees, as well as a larger BAI. Magnesium showed moderate differences during this time period.

4.2. Soil Samples

Soil chemical data from the control (WS7) and treatment (WS3) watersheds had some significant ($\alpha < 0.05$) differences as shown in Table 4.10. WS3 had lower pH, as well as available P and K in both the A and B horizons compared to WS7. Available calcium was significantly lower in the A horizon of WS3, as well as available Cu, Ni and Cd. In contrast, available Fe was significantly higher on WS3 in the A horizon. The B horizon contained moderately significant ($\alpha < 0.10$) differences for available Ni, Mn, and CEC, all of which were lower on the treatment watershed WS3 compared to the control WS7. While not significant, it should be noted that WS3 had a higher mean available Al concentration in the A horizon and a lower N content in both horizons.

Table 4.10. Plant-available elements from soil samples by soil horizons collected from control (WS7) and treatment (WS3) watersheds. Mean (M) concentrations (mg kg^{-1}) are shown except for pH and cation exchange capacity (CEC, meq 100 g^{-1}) with associated standard deviations (s).

Test	Stat	HZN	WS7	WS3		Test	Stat	HZN	WS7	WS3
			n=25	n=25					n=25	n=25
pH	M	A	4.68	4.29**		Mn	M	A	173.96	142.56
	s		0.40	0.20			s		106.22	95.82
	M	B	4.85	4.64**			M	B	48.69	31.55*
	s		0.23	0.13			s		35.16	24.26
P	M	A	16.82	10.38**		Fe	M	A	223.86	336.48**
	s		8.21	8.80			s		119.21	119.25
	M	B	6.52	4.14**			M	B	58.15	66.97
	s		4.65	1.84			s		30.84	63.79
CEC	M	A	14.60	14.30		Ni	M	A	1.61	0.70**
	s		1.83	2.88			s		2.00	0.43
	M	B	10.01	8.42**			M	B	0.55	0.49*
	s		2.95	1.62			s		0.17	0.04
K	M	A	77.42	64.59**		Cu	M	A	1.78	1.24**
	s		26.40	15.60			s		0.66	0.52
	M	B	42.70	32.84**			M	B	0.72	0.63
	s		17.00	9.24			s		0.30	0.24
Mg	M	A	33.63	25.02		Zn	M	A	9.12	7.82
	s		24.93	8.96			s		7.05	8.08
	M	B	25.81	18.77			M	B	1.83	2.18
	s		23.76	3.91			s		1.53	1.37
Ca	M	A	257.80	106.70**		Cd	M	A	0.27	0.21**
	s		364.30	42.70			s		0.12	0.05
	M	B	119.30	56.90			M	B	0.21	0.19
	s		198.20	27.00			s		0.06	0.03

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Table 4.10 (continued)

Test	Stat	HZN	WS7	WS3		Test	Stat	HZN	WS7	WS3
			n=25	n=25					n=25	n=25
Na	M	A	31.31	34.45		Pb	M	A	9.22	10.86
	s		11.41	4.26			s		4.76	6.86
	M	B	28.52	34.99			M	B	2.28	2.28
	s		5.56	18.97			s		1.13	2.04
Al	M	A	169.13	186.28		N	M	A	4514.00	3953.00
	s		47.89	38.99			s		1345.00	1513.00
	M	B	226.75	225.81			M	B	1468.90	1207.60
	s		53.51	44.25			s		852.00	607.30

* indicates significance at $\alpha < 0.10$ between control WS7 and treatment WS3 within the horizon, ** at $\alpha < 0.05$.

Chapter 5

DISCUSSION

5.1. Tree-Ring Element Concentration Differences

Ammonium sulfate supplies excess anions to the watershed directly in the form of SO_4^{2-} and indirectly through the nitrification of NH_4^+ to NO_3^-. As anions leach down through the soil profile cations become paired with them to retain electrical neutrality. As a result, specific cations are removed from soil exchange complexes to maintain charge balance in solution in the order given by the lyotropic series (Bohn et al. 1985)

$$Na^+ > K^+ \approx NH_4^+ > Mg^{2+} > Ca^{2+} > Sr^{2+} > Al^{3+}.$$

Cations removed from the exchange complexes can then be taken up by plants, become complexed with other anions and precipitate, rejoin the exchange complex somewhere else in the profile, or be leached from the soil profile.

Results of tree-ring chemistry data presented in Section 4.1 indicate that many of the cations made available by excess anion inputs appear to have been taken up by trees on the treatment watershed and deposited in tree rings, especially for black cherry and yellow-poplar. Black cherry had higher concentrations of K, Ca, and Sr associated with the ammonium sulfate treatment during the Treatment period (1989-1992) and also had a greater Mg concentration during Pre-treatment I (1986-1988) when compared to trees from the control watershed. Similar results were found by DeWalle et al. (1991) when testing black cherry trees from sites with a range of soil acidities. Yellow-poplar demonstrated similar results to black cherry for greater cation uptake in treatment trees compared to control trees.

Additional evidence for cation leaching is provided by Adams et al. (1995). They reported an increase in NO_3^- export in streamflow for WS3 compared to WS7. Although not significant due to variability, the authors reasoned that a nitrate export was occurring because the pre-treatment calibration period showed lower nitrate export for WS3 than WS7. The ammonium sulfate treatment raised the export of NO_3^- on WS3 to the equivalent of WS7. Adams et al. (1993) came to the same conclusion for nitrate export, but also found export of Ca to be significantly greater for WS3 compared to WS4, a mature-forested control basin. Increased Ca export was attributed to the pairing of Ca cations with nitrate anions (i.e., cation leaching). Similar results were obtained from Bear Brook Watershed in Maine that was also subjected to an ammonium sulfate treatment (Kahl et al. 1993). My own soil sampling in 1995, to be discussed later, also revealed significant soil differences between WS3 and WS7, which corroborated stream export and tree-ring chemistry data.

Anions showed differences between the watersheds and tree species. Higher S concentrations in both yellow-poplar and black cherry can be attributed to sulfur added by the ammonium sulfate treatment. Phosphorous was found to be significantly greater in black cherry trees from the treatment WS3 compared to control WS7, but yellow-poplar concentrations were not different between the watersheds.

An increase in trace metals (B, Cu, Mn, Fe, Al, Zn) is generally associated with increasing soil acidity (Pritchett and Fisher 1987). Boron, a metalloid, was the only element among these that showed higher concentrations in the treatment black cherry trees compared to controls. These differences occurred during all three sample periods. Zinc showed significantly higher concentrations during the Pre-treatment I sample period only. However, Fe, Al and Cu showed lower concentrations in treatment trees compared to control trees which is contrary to expectations. In addition, Mn concentrations in treatment black cherry and yellow-poplar were much lower compared to control black cherry trees.

Yellow-poplar seems to have had higher uptake of trace metals to a greater extent than black cherry, with the exception of Mn. Boron and Fe showed significantly higher concentrations in treatment yellow-poplar trees during Pre-treatment I and II sample periods, indicating greater uptake due to treatment. Both Zn and Al had higher mean concentrations in treatment trees, but results were not significant.

Large Mn concentration differences occurred between control and treatment samples of both black cherry and yellow-poplar trees. As noted above, Mn concentrations should become higher with higher soil acidity. DeWalle et al. (1991) found significantly higher Mn in black cherry tree rings from acidic Pea Vine Hill compared to a less acidic Fork Mountain site.

Since significant Mn deficiencies in yellow-poplar occurred even during the Pre-treatment III period, it is possible that pre-treatment Mn differences occurred between sites. Median heartwood age of treatment trees at the time of sampling was determined to be 1982 for yellow-poplar (Appendix, Table A.7) and 1983 for black cherry (Appendix, Table A.1). Thus, some or all of the Pre-treatment III sample (1976-1980) could have been heartwood at the time treatment was initiated. This would imply that the Mn differences are the result of differences between the watersheds themselves prior to treatment and not a product of ammonium sulfate treatment effects. Pickens (1995) found a significantly lower Mn concentration in the soil A horizon of treated plots within the Clover Run watershed, WS9. This watershed underwent the same ammonium sulfate treatment for an even longer period of time than WS3 in this study. The soil I collected in 1995 showed a similar result as Pickens', with significantly lower Mn concentrations in the B horizon of treatment WS3 compared to control WS7. The A horizon of WS3 also had lower Mn, but the difference was not significantly different from WS7.

It would not be expected to see a higher Mn concentrations associated with the ammonium sulfate treatment in the tree-rings on WS3 due to the existing low pH on the site. The pH difference between WS3 (4.29) and WS7 (4.68), while significant, is not large. Thus, Mn availability on WS3 probably would not become much higher relative to WS7 because the availability is already high at this pH (Bohn et al. 1985). In addition, the ammonium acts as a weak base in the soil (Bohn et al. 1985) and may help to buffer the soil of WS3 against large differences in pH.

Another possible explanation of lower trace metal concentrations, such as Mn, is greater availability of base cations. The movement of an ion from soil to root is determined in part by the concentration of other ions in the soil solution (Kramer and Kozlowski 1979). Concentrations of base cations were probably much higher in the soil solution due to the effects of cation leaching. These concentrations would greatly exceed the concentrations of trace metals thus reducing the availability of these metals at the soil-root interface for subsequent plant uptake.

Results from red maple samples were very different than the other two diffuse-porous species studied. With the exception of S and Fe concentrations, all other significant differences found were contrary to expectations and different from results with the other two diffuse-porous species studied. It is unclear why this would be the case, but the wide range of sites upon which red maple is found growing, from nutrient-rich to nutrient-poor, indicate it is a very adaptable species (Harlow et al. 1978).

Unlike sugar maple, I did not find any published tree-ring chemistry research using red maple, but it has been studied in a general sense. The foliage of red maple appears to absorb nutrients in significant amounts when compared to control trees (Adams et al. 1995; Pickens 1995).

In addition, Adams et al. (1995) also found no significant difference between Ca and N concentrations in the bolewood of treated red maple trees on WS3 compared to controls on WS7. Tree-ring concentration data from this study showed significantly ($\alpha < 0.10$) lower Ca in treatment trees during the Pre-treatment I period compared to the control trees. Also, a significantly ($\alpha < 0.05$) lower mean N concentration was found during the Treatment period compared to the control trees.

Because pre-treatment red maple tree-ring samples were not available, I cannot say with certainty whether or not red maple is good for tree-ring chemistry research. The results I found may be normal for red maple, or the concentrations may have even become higher in response to the ammonium sulfate treatment. However, the associated response of black cherry and yellow-poplar to the ammonium sulfate treatment seems to suggest a lack of tree-ring chemistry response in red maple. More research is needed to more accurately assess the potential of red maple in tree-ring chemistry research.

5.2. Expression of Tree-ring Chemistry Results

5.2.1. Element Molar Ratios

When concentration results of tree-ring chemistry were expressed as molar ratios, many significant differences were found for black cherry and yellow-poplar, but not red maple (Section 4.1.2.). In general, these differences, as well as the one moderately significant ($\alpha < 0.10$) difference found for red maple, appear to mimic the significant differences found for the individual concentration results of these species (Section 4.1.1.).

Some differences between concentration results and ratio results were noted, however. For example, black cherry Mg:Al ratios showed a significant difference between control and treatment trees during the Treatment period (1989-1992), but there were no differences found in these elemental concentrations when analyzed separately during the same time period (Table 4.1). Differences between the Ca:Sr molar ratio (Table 4.4) and Ca and Sr concentrations in black cherry were also observed. Concentration results were significantly different between treatment and control for both Ca and Sr during all time periods in black cherry (Table 4.1), but no difference was found in the Ca:Sr ratio during the Pre-treatment I sample period (1986-1988).

One interpretation of the varying significance of the Ca:Sr molar ratios in black cherry over time (Table 4.4) would be higher Ca uptake relative to Sr uptake on the treatment watershed (WS3) during the ammonium sulfate treatment. This is suggested by the declining Ca:Sr ratios in treatment trees (WS3) relative to control trees (WS7) over time. During the Pre-treatment II period (1981-1985), the Ca:Sr ratio was significantly higher for treatment trees compared to control trees, but this difference disappears during the Pre-treatment I period (1986-1988) and treatment trees end up with a significantly lower Ca:Sr ratio compared to control trees during the Treatment period (1989-1992).

Essentially, Sr appears to have increased in treatment trees over time faster than in control trees, even though both appear to have increasing Ca:Sr ratios with time. Molar ratios of elements could be beneficial in the use of detecting changes in soil chemistry over time if the ratios were constant over time in control trees, but not in treatment trees. This would be an advantage because a simple change in a molar ratio might indicate a significant change in the soil chemistry that may adversely affect tree growth, as well as indicate the time of the soil change. However, ratios appear to change with time in both control and treatment trees and a simple ratio change by itself is not an indication of soil change, so more evidence would be needed.

Yellow-poplar also displayed differences between Ca and Al concentration results and the Ca:Al molar ratio. This ratio was not significantly different during the Treatment and Pre-treatment I sample periods (Table 4.6), but Ca concentrations were significantly different between treatment and control during these time periods (Table 4.3). The examples of yellow-poplar and black cherry molar ratios indicate that some molar ratios may show different results than concentrations alone which may assist the researcher in interpreting tree-ring chemistry results.

From this discussion, I conclude that concentrations are better than element molar ratios when expressing results for this study. While some molar ratios show promise for detecting soil differences, especially Ca:Al and Ca:Sr, the majority of ratios mimic the results obtained by using concentrations alone. This conclusion is based on data collected for this study only, and does not necessarily hold for all studies of tree-ring chemistry.

5.2.2. BAI x Concentration Loads

Results of BAI x concentration data from all three species were not consistent with expectations of an ammonium sulfate treatment. Unlike concentrations alone, multiplying by BAI yielded higher values in control trees compared to treatment trees. If these results were to be taken as valid, then the conclusion would be that the ammonium sulfate treatment significantly reduced the uptake of all analyzed elements in treatment trees compared to control trees.

The reason behind multiplying BAI times the concentration was to simulate the "elemental burdens" first described by Baes and McLaughlin (1984). Their technique was to multiply concentrations by the gram sample weight in order to factor out growth differences among watersheds. In this study, sample weights were not comparable due to the technique used to obtain samples from the wood discs. As a result, an unknown volume of material was obtained for each sample, unlike using an increment corer which provides a fixed radius for all cores.

In addition, element burdens based upon radial growth rates do not consider the influence of basal area growth. Radial growth rates normally diminish in older trees even when basal area increment is still increasing due to larger diameters. Multiplying BAI x concentration indexes the mass of the element added around the entire circumference of the tree. BAI is considered to be a good index for the amount of wood produced when using dendrochronological analyses (Jordan et al. 1990).

Obtaining an estimate of the element mass for the entire tree may be useful for studies where a nutrient budget approach is being used. However, the objective of this study was to assess whether or not tree-ring chemistry is useful in detecting chemical differences associated with an ammonium sulfate treatment. For this purpose, a relative measure of element content in tree rings is more appropriate due to the comparison to tree rings obtained from a control watershed, which is what element content expressed as a concentration provides.

5.3. Temporal Resolution of Tree-ring Chemistry

Despite the apparent usefulness of black cherry and yellow-poplar tree rings in detecting soil chemistry associated with ammonium sulfate treatment, the timing of these differences is not readily noticeable using concentrations. This is due to the well-known problems of sapflow and radial translocation of elements, as well as the young trees available in the study area. Cutter and Guyette (1993) provide an extended description of the properties necessary to provide accurate and reproducible results in dendrochemical studies. They note that diffuse porous trees can have as many as 100+ rings participating in sapflow. Thus, while a significant chemical change may occur during a particular year, that change may appear to be several years earlier due to sapflow occurring in tree rings formed in prior years. In my study, significant differences occurred for many elements in rings formed before treatment was initiated in 1992, implicating sapflow and/or element mobility complications.

In addition to the question of sapflow, there is also the question of mobility of elements once they are deposited in the tree rings. Cutter and Guyette (1993) provide a list of potential mobilities of elements based on solubility, ionic-charge ratio, and essential nature. Moderate movement is thought to occur for Ca, Sr, Mn, Zn, Rb, Cu, and Mo, while heavy metals such as Pb, Ni, Fe, and Al are considered to have low mobility. Elements such as N, P, and K are known to move from areas of low usage to areas with high demand. This may partially explain the significantly higher P concentrations noted above.

The presence of heartwood also affects the radial movement of elements. Potential movement of elements in the heartwood of some tree species is dependent on the permeability and moisture content of the wood (Cutter and Guyette 1993). Cutter and Guyette concluded that yellow-poplar, a species used in my study, generally has sufficiently low heartwood permeability to benefit dendrochemistry work. On the other hand, high moisture content in the heartwood detracts from its use. In addition, the relatively young age at which these trees were sampled raises doubt as to when the heartwood was formed in black cherry and yellow-poplar prior to treatment on WS3 and its relationship to time of tree sampling.

5.4. Sample Size Estimates

McClenahen et al. (1987, 1989) suggested a general strategy of sampling more trees after obtaining two cores per tree to obtain an adequate sample size. My study utilized only five trees from each watershed. In order to assess the adequacy of this sample size, I estimated the sample size required to achieve within 10% of the calculated mean of Pre-treatment I element concentrations from Tables 4.1 to 4.3, with $\alpha = 0.10$ and various degrees of certainty (Table 5.1). This table indicates that black cherry and yellow-poplar require much larger sample sizes than that used in this study and much lower sample sizes are needed for red maple trees to attain the same degree of certainty. Interestingly, a low number of samples is needed to estimate the mean of B for all three species, indicating very little variation of that element between trees.

Table 5.1. Estimated sample sizes required to obtain mean element concentrations within 10% of the calculated mean of five trees.

Element	Black Cherry		Red Maple		Yellow Poplar	
	90% certainty	80% certainty	90% certainty	80% certainty	90% certainty	80% certainty
P	190*	100	19	10	346	182
K	73	39	18	10	42	22
Ca	135	71	5	3	42	22
Mg	236	124	19	10	7	4
Mn	350	184	117	62	327	171
Fe	633	332	189	100	309	162
Cu	44	23	82	43	13	7
B	12	7	4	2	4	2
Al	1846	968	1	1	35	19
Zn	201	106	208	109	47	25
Na	355	187	1009	530	72	38
Sr	42	22	23	12	40	21
N	23	12	37	20	177	93
S	13	7	11	6	30	16

* Calculations made using means and standard deviations from Pre-treatment I samples with $\alpha = 0.10$.

5.5. Plant-available Soil Chemistry

Additional evidence for differences between the control WS7 and treatment WS3 associated with the ammonium sulfate treatment is provided by the soil samples collected in 1995. Major cations Ca and K were significantly lower in the soil on the treated watershed in 1995 compared to the control WS7, possibly indicating cation leaching from the watershed and/or plant uptake. Also, the pH on WS3 was significantly lower in 1995. In contrast, results from Gilliam et al. (1994) showed no pH difference in soil between WS3 and WS7 in 1992. It should be noted that Gilliam obtained composite samples from 0-10 cm depth. In my study, two horizons were sampled instead of sampling to a specific depth. The average sampling depth of the A horizon in this study was 5.9 cm on WS3 and 7.0 cm on WS7. The B horizon had average depths of 18.6 and 22.1 cm for WS3 and WS7, respectively. Thus, the results of my study and Gilliam et al. (1994) may not be directly comparable.

While Fe was significantly ($\alpha < 0.05$) greater in the A horizon on WS3 compared to the control WS7, Cu and Cd were significantly lower in the A horizon and Mn was significantly ($\alpha < 0.10$) lower in the B horizon. While not significantly different, Zn was also lower in the A horizon on WS3. These soil data suggest a difference between the two watersheds before the ammonium sulfate treatment began because metals would be expected to be greater on WS3 due to the treatment.

Additional evidence for differences between the watersheds prior to treatment was the conclusion by Adams et al. (1995) that nitrate exports on WS3 were lower than WS7 nitrate export during the calibration period before treatment began. From this and previous evidence, it appears that differences in chemical elements due to factors other than the ammonium sulfate treatment were possible between treatment (WS3) and control (WS7) soil and tree-ring chemistry.

Chapter 6

SUMMARY AND CONCLUSIONS

Hypothesis 1. Three years of ammonium sulfate treatment designed to apply double the annual atmospheric inputs on treatment watershed (WS3) at the Fernow Experimental Forest was associated with elemental differences in the tree-ring chemistry of black cherry and yellow-poplar when compared to tree-ring chemistry from control WS7. The null hypothesis is rejected for these species. Significantly higher ($\alpha <$ .05) S in black cherry and yellow-poplar most likely due to fertilization were found during the Treatment period (1989-1992). Significantly higher tree-ring concentrations of Ca, Mg, and K in both species suggest cation mobilization due to leaching of excess nitrates through the soil profile and into stream flow.

Boron and Sr were also found to be significantly greater in treatment (WS3) trees compared to control (WS7) trees. Manganese was found to be lower in both species compared to control trees, which is inconsistent with process of acidification and may be due to pre-existing soil differences between watersheds. Since no pre-treatment tree-ring chemistry data exists for this area, it is not possible to determine with certainty whether tree-ring element concentrations changed or not due to the ammonium sulfate treatment.

Red maple trees showed results different from yellow-poplar and black cherry. Red maple tree rings showed significantly lower P, K, Na, N, and S concentrations in treatment (WS3) trees compared to control (WS7) trees. Results suggest red maple is not an appropriate species for tree-ring chemistry research, but again a definitive conclusion cannot be drawn without pre-treatment tree-ring chemistry data.

Hypothesis 2. Analysis using element loads, or concentrations multiplied by basal area growth increment (BAI) values, yielded significant differences for almost all sample periods and elements for all species. Since the objective of my study was to assess the ability of tree-ring chemistry to detect chemical differences associated with soil acidification, concentrations provided relative element amounts in tree rings for comparison to control tree rings. Element loads would probably be useful for nutrient budget studies.

Comparison of elemental molar ratios also showed significant differences between treatment and control trees, but appeared to largely mimic concentration results, with the exception of Ca:Sr and Mg:Al for black cherry and Ca:Al for yellow-poplar. The null hypothesis is accepted that concentration results are the best way to show results for this study. However, the Ca:Sr ratio in black cherry and Ca:Al ratio in yellow-poplar deserve additional research over longer time periods in older trees.

Hypothesis 3. Complex problems of sapflow in tree rings formed prior to treatment and element translocation negated the use of black cherry, red maple, and yellow-poplar concentrations in determining the precise timing of differences in soil chemistry by comparing control and treatment trees. Significant differences in tree-ring element concentrations between treatment and control were found in rings formed up to thirteen years prior to treatment. Thus, the null hypothesis is accepted. Until these problems are studied in depth for these and other species, the utility of tree-ring chemistry is limited to assessing if soil changes occur, but not the exact time of these changes. Molar ratios of Ca:Sr in black cherry and possibly Ca:Al in yellow-poplar may be able to aid the investigator in detecting the timing of sudden soil changes. More research with a variety of soil amendments over longer time periods may produce better temporal detection ability.

Hypothesis 4. Significant differences exist in available soil elements between control and treatment watersheds. The null hypothesis is rejected. Calcium and pH were significantly lower in the upper horizons of the treated watershed (WS3) compared to the control (WS7). Potassium, Ni and P were significantly lower in both the A and B horizons, while Mn was lower in the B horizon of the treatment watershed WS3. Significantly lower concentrations of Ni, Cu, and Cd were found on the treatment (WS3) watershed when compared to the control (WS7) watershed. It cannot be determined for certain if these differences were due to the ammonium sulfate treatment or if they existed before the treatment began; however, changes suggest base cation leaching in response to treatment.

Chapter 7

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Appendix

DATA TABLES

Table A.1. General data for sampled black cherry trees and tree-ring segments collected from control (WS7) and treatment (WS3) watersheds at Fernow Experimental Forest in 1992. WS = watershed, DBH = diameter at breast height, HTWD Year = last year of heartwood formation, Width = average sample width, BAI = basal area increment.

WS	Tree No.	DBH (cm)	Quadrant	Sample Years	Sample ID	HTWD Year	Width (mm)	BAI (cm^2)
WS7	1	14.478	A	1989-1992	1A1		7.85	8.00
			A	1986-1988	1A2	1986	10.77	9.40
			A	1981-1985	1A3		25.32	14.93
			B	1989-1992	1B1		13.35	13.03
			B	1986-1988	1B2	1987	8.82	7.08
			B	1981-1985	1B3		18.35	10.80
			C	1989-1992	1C1		9.79	9.83
			C	1986-1988	1C2	1988	8.08	6.98
			C	1981-1985	1C3		23.43	14.44
			D	1989-1992	1D1		18.53	17.34
			D	1986-1988	1D2	1987	9.72	6.93
			D	1981-1985	1D3		31.40	12.27
WS7	2	20.574	A	1989-1992	2A1		21.67	29.64
			A	1986-1988	2A2	1987	22.52	22.99
			A	1981-1985	2A3		38.13	20.76
			B	1989-1992	2B1		17.25	24.20
			B	1986-1988	2B2	1988	20.72	22.88
			B	1981-1985	2B3		34.23	23.02
			C	1989-1992	2C1		19.19	26.62
			C	1986-1988	2C2	1987	18.45	20.14
			C	1981-1985	2C3		34.07	23.14

(Continued on next page)

Table A.1 (continued)

WS	Tree No.	DBH (cm)	Quadrant	Sample Years	Sample ID	HTWD Year	Width (mm)	BAI (cm^2)
WS7	2	20.574	D	1989-1992	2D1		17.43	24.42
			D	1986-1988	2D2	1987	15.53	17.73
			D	1981-1985	2D3		27.36	22.03
WS7	3	18.034	A	1989-1992	3A1		22.77	26.83
			A	1986-1988	3A2	1986	18.96	16.12
			A	1981-1985	3A3		20.95	11.25
			B	1989-1992	3B1		22.16	26.22
			B	1986-1988	3B2	1986	18.25	15.80
			B	1981-1985	3B3		20.66	11.57
			C	1989-1992	3C1		19.66	23.64
			C	1986-1988	3C2		16.18	14.91
			C	1981-1985	3C3	1985	23.78	14.45
			D	1989-1992	3D1		15.35	18.98
			D	1986-1988	3D2		13.33	13.48
			D	1981-1985	3D3	1985	25.23	17.88
WS7	4	20.574	A	1989-1992	4A1		17.95	25.13
			A	1986-1988	4A2	1986	14.86	16.97
			A	1981-1985	4A3		42.74	29.49
			B	1989-1992	4B1		20.55	28.35
			B	1986-1988	4B2		13.17	14.68
			B	1981-1985	4B3		28.44	22.41
			C	1989-1992	4C1		18.27	25.54
			C	1986-1988	4C2		13.25	15.24
			C	1981-1985	4C3		26.88	22.44
			D	1989-1992	4D1		16.93	23.83
			D	1986-1988	4D2	1986	13.98	16.29
			D	1981-1985	4D3		31.01	25.18
WS7	5	20.828	A	1989-1992	5A1		12.82	18.66
			A	1986-1988	5A2		13.58	16.95
			A	1981-1985	5A3	1984	36.32	31.09
			A	1976-1980	5A4		26.85	9.66
			B	1989-1992	5B1		14.77	21.26
			B	1986-1988	5B2		11.97	14.72
			B	1981-1985	5B3	1984	22.46	21.55
			B	1976-1980	5B4		21.20	13.08
			C	1989-1992	5C1		10.92	16.06
			C	1986-1988	5C2		17.19	21.48
			C	1981-1985	5C3	1985	34.00	28.81
			C	1976-1980	5C4		24.86	9.57
			D	1989-1992	5D1		19.77	27.69

(Continued on next page)

Table A.1 (continued)

WS	Tree No.	DBH (cm)	Quadrant	Sample Years	Sample ID	HTWD Year	Width (mm)	BAI (cm^2)
WS7	5	20.828	D	1986-1988	5D2		15.43	17.35
			D	1981-1985	5D3	1983	35.66	25.79
			D	1976-1980	5D4		21.78	5.92
WS3	6	19.05	A	1989-1992	6A1		7.75	10.56
			A	1986-1988	6A2		6.77	8.45
			A	1981-1985	6A3	1983	17.37	18.39
			A	1976-1980	6A4		25.96	18.65
			B	1989-1992	6B1		12.73	16.84
			B	1986-1988	6B2		7.96	9.24
			B	1981-1985	6B3	1983	18.07	17.28
			B	1976-1980	6B4		26.01	15.87
			C	1989-1992	6C1		12.85	16.99
			C	1986-1988	6C2		9.17	10.54
			C	1981-1985	6C3	1983	15.56	14.86
			C	1976-1980	6C4		35.96	19.80
			D	1989-1992	6D1		7.29	9.96
			D	1986-1988	6D2		6.80	8.54
			D	1981-1985	6D3	1983	16.35	17.55
			D	1976-1980	6D4		29.67	21.13
WS3	7	18.288	A	1989-1992	7A1		6.13	8.17
			A	1986-1988	7A2		5.24	6.51
			A	1981-1985	7A3	1983	16.90	18.07
			A	1976-1980	7A4		25.00	18.51
			B	1989-1992	7B1		7.14	9.45
			B	1986-1988	7B2		5.04	6.19
			B	1981-1985	7B3	1984	14.83	15.91
			B	1976-1980	7B4		19.66	15.77
			C	1989-1992	7C1		7.23	9.58
			C	1986-1988	7C2		8.14	9.80
			C	1981-1985	7C3	1985	20.86	20.35
			C	1976-1980	7C4		21.38	13.76
			D	1989-1992	7D1		3.86	5.22
			D	1986-1988	7D2		3.97	5.12
			D	1981-1985	7D3	1983	20.12	22.13
			D	1976-1980	7D4		41.10	25.44
WS3	8	17	A	1989-1992	8A1		4.60	5.63
			A	1986-1988	8A2		6.48	7.37
			A	1981-1985	8A3	1983	17.90	16.93
			A	1976-1980	8A4		17.89	11.90

(continued on next page)

Table A.1 (continued)

WS	Tree No.	DBH	Quadrant	Sample	Sample	HTWD	Width	BAI
		(cm)		Years	ID	Year	(mm)	(cm^2)
WS3	8	17	B	1989-1992	8B1		5.67	6.89
			B	1986-1988	8B2		6.77	7.57
			B	1981-1985	8B3	1984	13.06	12.57
			B	1976-1980	8B4		18.99	13.50
			C	1989-1992	8C1		4.58	5.61
			C	1986-1988	8C2		6.93	7.86
			C	1981-1985	8C3	1983	17.80	16.73
			C	1976-1980	8C4		18.35	12.04
			D	1989-1992	8D1		7.72	9.26
			D	1986-1988	8D2		6.83	7.41
			D	1981-1985	8D3	1984	18.62	16.49
			D	1976-1980	8D4		18.01	10.78
WS3	9	17.526	A	1989-1992	9A1		11.42	13.91
			A	1986-1988	9A2		11.99	12.40
			A	1981-1985	9A3	1985	27.90	20.12
			A	1976-1980	9A4		25.12	7.65
			B	1989-1992	9B1		4.90	6.22
			B	1986-1988	9B2		6.73	7.93
			B	1981-1985	9B3	1984	14.77	14.90
			B	1976-1980	9B4		22.98	16.38
			C	1989-1992	9C1		6.46	8.12
			C	1986-1988	9C2		6.73	7.77
			C	1981-1985	9C3	1981	17.78	17.09
			C	1976-1980	9C4		20.36	13.47
			D	1989-1992	9D1		16.20	19.12
			D	1986-1988	9D2	1986	10.41	10.12
			D	1981-1985	9D3		25.47	17.57
			D	1976-1980	9D4		25.54	7.39
WS3	10	15.24	A	1989-1992	10A1		6.07	6.60
			A	1986-1988	10A2		3.63	3.67
			A	1981-1985	10A3	1982	20.16	16.62
			A	1976-1980	10A4		26.51	12.14
			B	1989-1992	10B1		3.63	4.02
			B	1986-1988	10B2		3.55	3.72
			B	1981-1985	10B3	1982	13.80	12.61
			B	1976-1980	10B4		12.51	8.85

(continued on next page)

(Table A.1 continued)

WS	Tree No.	DBH (cm)	Quadrant	Sample Years	Sample ID	HTWD Year	Width (mm)	BAI (cm^2)
			C	1989-1992	10C1		2.66	2.96
			C	1986-1988	10C2		2.78	2.98
			C	1981-1985	10C3	1981	13.54	12.78
			C	1976-1980	10C4		16.51	11.68
			D	1989-1992	10D1		4.85	5.32
			D	1986-1988	10D2		4.57	4.67
			D	1981-1985	10D3	1982	16.89	14.43
			D	1976-1980	10D4		27.34	13.87

Table A.2. Tree-ring chemistry data (P, K, Ca, Mg, Mn, Fe, Cu) for black cherry trees collected from control (WS7) and treatment (WS3) watersheds at Fernow Experimental Forest.

Sample	Sample	P	K	Ca	Mg	Mn	Fe	Cu
ID	Years	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
1A1	1989-1992	140	860	430	100	67	32	2
1A2	1986-1988	60	360	350	80	61	27	1.4
1A3	1981-1985	140	1370	360	110	22	5	1.5
1B1	1989-1992	140	1370	680	160	108	10	1.9
1B2	1986-1988	40	290	270	70	48	7	1.2
1B3	1981-1985	10	200	180	30	24	10	1.2
1C1	1989-1992	140	1160	600	210	114	14	2.2
1C2	1986-1988	30	400	240	70	38	7	1.4
1C3	1981-1985	20	180	220	60	37	12	1.3
1D1	1989-1992	100	760	390	80	67	7	1.7
1D2	1986-1988	30	260	210	40	36	7	1.6
1D3	1981-1985	10	140	140	20	20	6	1.2
2A1	1989-1992	210	1180	560	120	73	32	3.2
2A2	1986-1988	30	220	180	30	26	13	1.4
2A3	1981-1985	10	140	130	10	20	5	1.3
2B1	1989-1992	140	1060	390	120	70	9	2
2B2	1986-1988	20	240	140	20	20	8	1.5
2B3	1981-1985	20	170	150	20	19	10	2.3
2C1	1989-1992	120	1020	410	100	68	9	1.8
2C2	1986-1988	30	280	240	40	35	8	1.5
2C3	1981-1985	10	140	160	20	20	6	1.3
2D1	1989-1992	120	1020	480	110	64	6	2.4
2D2	1986-1988	40	330	260	40	38	6	1.3
2D3	1981-1985	10	140	160	20	25	6	1.5
3A1	1989-1992	120	1270	480	130	127	18	2
3A2	1986-1988	50	370	350	70	93	11	1.8
3A3	1981-1985	10	180	190	30	46	5	1.8
3B1	1989-1992	100	840	350	100	92	9	1.6
3B2	1986-1988	60	400	360	70	96	7	1.9
3B3	1981-1985	10	180	150	20	38	9	2
3C1	1989-1992	110	1020	380	90	86	6	1.9
3C2	1986-1988	70	430	430	80	119	5	1.6
3C3	1981-1985	20	160	160	20	41	6	1.8
3D1	1989-1992	110	1050	380	110	78	6	1.7
3D2	1986-1988	70	460	440	80	121	5	1.8
3D3	1981-1985	20	200	190	20	49	4	1.8
4A1	1989-1992	110	920	360	80	79	12	1.5
4A2	1986-1988	50	310	360	50	75	8	1.3

(continued on next page)

Table A.2 (continued)

Sample ID	Sample Years	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
4A3	1981-1985	10	150	160	20	31	4	0.9
4B1	1989-1992	110	980	370	80	69	7	1.5
4B2	1986-1988	50	330	390	60	93	7	1.2
4B3	1981-1985	10	160	160	20	34	6	1.1
4C1	1989-1992	110	1010	380	70	73	7	1.5
4C2	1986-1988	50	320	380	60	94	5	1.2
4C3	1981-1985	10	160	160	20	36	5	0.8
4D1	1989-1992	110	1030	380	80	69	6	1.5
4D2	1986-1988	50	390	360	50	80	7	1.2
4D3	1981-1985	10	180	160	20	35	5	1.1
5A1	1989-1992	100	840	400	80	54	9	1.7
5A2	1986-1988	70	430	440	110	71	7	1.8
5A3	1981-1985	20	160	130	20	19	6	2.7
5A4	1976-1980	10	180	150	20	18	7	6.3
5B1	1989-1992	110	960	410	80	51	8	1.6
5B2	1986-1988	70	440	430	90	65	7	1.4
5B3	1981-1985	30	210	180	30	27	4	1.6
5B4	1976-1980	10	160	140	10	18	6	3.2
5C1	1989-1992	120	1010	390	80	62	7	1.8
5C2	1986-1988	70	430	380	90	58	4	1.7
5C3	1981-1985	10	150	140	20	18	5	3.1
5C4	1976-1980	10	170	150	20	19	9	4.3
5D1	1989-1992	120	940	410	80	56	5	2
5D2	1986-1988	70	430	420	100	62	6	1.8
5D3	1981-1985	10	130	120	10	16	5	3.3
5D4	1976-1980	10	130	140	20	18	6	5
6A1	1989-1992	150	1070	420	120	29	5	1.5
6A2	1986-1988	70	400	450	100	25	3	1.1
6A3	1981-1985	20	230	240	40	10	3	0.8
6A4	1976-1980	10	180	200	30	9	4	1
6B1	1989-1992	110	810	370	90	20	6	1.4
6B2	1986-1988	60	310	440	80	23	6	1.2
6B3	1981-1985	30	210	260	40	13	4	1.1
6B4	1976-1980	10	120	140	10	5	7	1
6C1	1989-1992	130	1040	410	10	20	11	1.4
6C2	1986-1988	60	320	440	80	18	8	1.4
6C3	1981-1985	30	180	270	30	11	6	1.1
6C4	1976-1980	10	110	150	10	5	7	1.2
6D1	1989-1992	130	1080	520	130	33	16	1.5
6D2	1986-1988	70	360	530	100	35	4	1
6D3	1981-1985	30	250	340	60	20	4	0.8
6D4	1976-1980	10	160	230	40	11	14	1.2

(continued on next page)

Table A.2 (continued)

Sample ID	Sample Years	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
7A1	1989-1992	160	1110	530	110	20	8	1.7
7A2	1986-1988	60	380	510	60	22	4	1.1
7A3	1981-1985	30	240	350	40	12	3	1
7A4	1976-1980	10	150	220	20	6	4	1.2
7B1	1989-1992	150	1250	550	90	17	9	1.9
7B2	1986-1988	60	400	550	70	17	7	1.2
7B3	1981-1985	30	250	390	50	12	5	1
7B4	1976-1980	10	240	280	20	9	6	1.1
7C1	1989-1992	140	1290	470	80	23	13	1.7
7C2	1986-1988	70	430	520	80	21	7	1.3
7C3	1981-1985	20	190	250	30	9	5	1.2
7C4	1976-1980	20	200	290	30	11	9	1.2
7D1	1989-1992	170	930	590	110	21	10	2.3
7D2	1986-1988	70	400	530	60	14	6	1.5
7D3	1981-1985	30	220	340	40	11	7	1.1
7D4	1976-1980	10	190	230	20	7	10	1.6
8A1	1989-1992	170	1320	550	140	24	5	1.7
8A2	1986-1988	70	470	510	130	23	3	1.2
8A3	1981-1985	30	270	340	80	15	2	1
8A4	1976-1980	10	160	250	40	9	5	0.9
8B1	1989-1992	160	1540	470	140	22	8	1.9
8B2	1986-1988	70	480	520	150	22	7	1.3
8B3	1981-1985	30	210	300	60	13	5	0.8
8B4	1976-1980	10	130	260	40	11	4	0.9
8C1	1989-1992	200	1850	570	160	21	7	2.5
8C2	1986-1988	70	450	500	140	18	4	1.4
8C3	1981-1985	30	200	310	70	12	3	0.9
8C4	1976-1980	10	140	250	40	9	4	1.1
8D1	1989-1992	150	1280	530	140	26	6	2.2
8D2	1986-1988	70	520	500	180	29	4	1.5
8D3	1981-1985	20	220	250	60	12	4	0.9
8D4	1976-1980	10	190	230	40	9	6	1.2
9A1	1989-1992	100	830	430	100	20	7	1.3
9A2	1986-1988	60	380	510	90	18	5	1.3
9A3	1981-1985	10	110	160	20	6	84	1.1
9A4	1976-1980	10	140	190	30	7	11	1.1
9B1	1989-1992	130	1240	510	100	17	6	1.7
9B2	1986-1988	60	380	530	80	20	5	1.2
9B3	1981-1985	30	190	330	50	11	4	0.8
9B4	1976-1980	10	140	280	40	8	6	0.9

(continued on next page)

Table A.2 (continued)

Sample ID	Sample Years	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
9C1	1989-1992	110	990	480	120	15	5	1.6
9C2	1986-1988	60	380	550	100	28	5	1.1
9C3	1981-1985	20	150	230	30	13	4	0.8
9C4	1976-1980	10	150	260	40	10	5	0.9
9D1	1989-1992	100	850	420	110	25	5	1.6
9D2	1986-1988	50	310	300	60	16	4	1.3
9D3	1981-1985	10	120	120	20	7	5	1
9D4	1976-1980	10	150	170	20	7	5	1.1
10A1	1989-1992	150	1160	540	120	21	69	1.8
10A2	1986-1988	70	440	540	100	23	5	1.5
10A3	1981-1985	40	330	470	100	21	4	1
10A4	1976-1980	10	200	350	60	14	4	1.4
10B1	1989-1992	180	1480	560	130	28	10	2
10B2	1986-1988	70	520	540	110	29	8	1.4
10B3	1981-1985	50	350	510	110	24	6	1.1
10B4	1976-1980	10	240	450	70	18	5	1.2
10C1	1989-1992	190	1860	580	140	26	6	2
10C2	1986-1988	80	630	530	90	27	5	1.3
10C3	1981-1985	50	420	470	110	26	3	1
10C4	1976-1980	10	210	380	60	16	3	1.2
10D1	1989-1992	140	1280	540	120	21	5	1.9
10D2	1986-1988	70	470	580	100	23	5	1.5
10D3	1981-1985	50	340	460	100	21	7	1
10D4	1976-1980	10	220	390	70	16	4	1.4

Table A.3. Additional tree-ring chemistry data (B, Al, Zn, Na, Sr, N, S) for black cherry trees collected from control (WS7) and treatment (WS3) watersheds at Fernow Experimental Forest.

Sample ID	Sample Years	B (ppm)	Al (ppm)	Zn (ppm)	Na (ppm)	Sr (ppm)	N (ppm)	S (ppm)
1A1	1989-1992	3.4	21	4.8	12	3.6	1510	86
1A2	1986-1988	2.6	14	2.4	8	3.3	1070	73
1A3	1981-1985	3.1	1	2.7	12	4.8	790	136
1B1	1989-1992	3.4	4	3.1	15	4.3	1690	88
1B2	1986-1988	2.4	2	1.1	8	3	880	60
1B3	1981-1985	2.6	2	6.5	11	2.8	660	58
1C1	1989-1992	5.1	2	2.4	15	4.2	1640	98
1C2	1986-1988	3.3	2	1.2	10	2.8	1070	67
1C3	1981-1985	2.5	1	1.6	10	2.8	930	58
1D1	1989-1992	2.9	2	2.1	19	3.3	1010	71
1D2	1986-1988	2.5	2	1.2	12	2.8	810	58
1D3	1981-1985	2.5	1	6.3	6	2.4	820	57
2A1	1989-1992	3.8	103	4.4	15	4.9	1580	103
2A2	1986-1988	2.4	7	1.4	5	2.8	980	64
2A3	1981-1985	2.3	1	1.5	4	2.4	600	56
2B1	1989-1992	4.2	3	2.2	8	3.5	1360	94
2B2	1986-1988	2.9	2	0.8	7	2.5	940	63
2B3	1981-1985	2.7	1	3.7	13	2.5	920	62
2C1	1989-1992	3.5	2	2.3	8	3.6	1230	79
2C2	1986-1988	2.5	2	1.3	6	3.3	800	59
2C3	1981-1985	2.4	1	1.1	9	2.8	710	63
2D1	1989-1992	3.2	1	2.4	12	4.4	1340	80
2D2	1986-1988	2.4	1	1	20	3.1	920	57
2D3	1981-1985	2.4	1	1.7	6	2.7	860	55
3A1	1989-1992	3.2	8	3	8	4.5	1430	89
3A2	1986-1988	2.8	5	1.9	8	3.8	1110	62
3A3	1981-1985	2.6	1	1.9	7	3	820	58
3B1	1989-1992	2.8	2	2.1	7	3.8	1110	82
3B2	1986-1988	2.9	2	1.7	9	3.7	790	66
3B3	1981-1985	2.7	2	1.2	11	2.6	740	68
3C1	1989-1992	3.3	2	2.5	7	3.7	1000	88
3C2	1986-1988	2.6	2	1.9	6	4	830	58
3C3	1981-1985	2.5	1	1.3	6	2.7	680	66
3D1	1989-1992	3.3	2	2.4	14	4.3	1080	80
3D2	1986-1988	2.9	1	2.5	13	4.1	850	63
3D3	1981-1985	2.6	1	2.5	7	2.9	890	63
4A1	1989-1992	3.3	4	3	9	3.2	1110	73

(continued on next page)

Table A.3 (continued)

Sample ID	Sample Years	B (ppm)	Al (ppm)	Zn (ppm)	Na (ppm)	Sr (ppm)	N (ppm)	S (ppm)
4A2	1986-1988	2.8	3	1.8	9	3.5	780	52
4A3	1981-1985	2.7	1	1.6	7	2.6	610	50
4B1	1989-1992	3.5	2	2.4	9	3.4	1030	74
4B2	1986-1988	2.8	3	2	10	3.3	860	57
4B3	1981-1985	2.7	1	1.5	6	2.4	670	55
4C1	1989-1992	3.5	3	2.8	11	3.4	1120	76
4C2	1986-1988	2.7	1	1.7	7	3.4	820	53
4C3	1981-1985	2.6	1	1.3	5	2.5	610	50
4D1	1989-1992	3.3	1	2.4	13	3.4	1100	76
4D2	1986-1988	2.7	2	3.3	20	3.5	830	56
4D3	1981-1985	2.9	1	4.5	5	2.8	710	49
5A1	1989-1992	3.4	3	2.1	6	4.3	1250	73
5A2	1986-1988	2.9	3	2	6	4.2	1010	56
5A3	1981-1985	2.6	1	3	7	2.5	620	58
5A4	1976-1980	2.8	1	5.4	10	2.9	640	59
5B1	1989-1992	3.2	3	2.2	15	4.1	1180	77
5B2	1986-1988	2.8	2	2	9	4	810	60
5B3	1981-1985	2.5	1	1.1	4	2.8	680	54
5B4	1976-1980	2.5	1	3.1	7	2.8	760	55
5C1	1989-1992	3.5	1	2.4	8	3.9	1220	85
5C2	1986-1988	2.8	1	1.5	7	3.9	870	57
5C3	1981-1985	2.9	1	1.6	6	2.7	730	63
5C4	1976-1980	2.8	1	2.7	7	3.1	700	69
5D1	1989-1992	3.3	2	2.1	12	4.4	1190	75
5D2	1986-1988	2.7	1	1.7	17	4.4	900	59
5D3	1981-1985	2.6	1	3.3	6	2.7	810	58
5D4	1976-1980	2.7	1	3.1	5	3	1010	81
6A1	1989-1992	4.1	1	2.3	7	4.2	1150	92
6A2	1986-1988	3.2	1	1.7	6	4.6	740	62
6A3	1981-1985	2.7	1	7.1	7	3.3	590	49
6A4	1976-1980	2.7	1	3.4	5	3	680	53
6B1	1989-1992	3.9	3	1.8	5	4	1110	83
6B2	1986-1988	2.7	2	1.3	7	4.4	800	58
6B3	1981-1985	2.6	1	0.8	6	3.6	640	50
6B4	1976-1980	2.5	1	0.7	5	2.9	630	50
6C1	1989-1992	4.1	2	2.3	7	4.5	990	82
6C2	1986-1988	2.8	2	1.3	7	4.9	640	63
6C3	1981-1985	2.7	1	0.9	6	3.9	670	53
6C4	1976-1980	2.4	2	24.3	8	2.9	630	58
6D1	1989-1992	3.7	1	2.7	7	5.2	1330	83
6D2	1986-1988	2.9	1	2.3	6	5.2	1120	65
6D3	1981-1985	2.7	1	1.8	5	3.8	1060	52

(continued on next page)

Table A.3 (continued)

Sample ID	Sample Years	B (ppm)	Al (ppm)	Zn (ppm)	Na (ppm)	Sr (ppm)	N (ppm)	S (ppm)
6D4	1976-1980	2.7	1	2.7	11	3.2	700	52
7A1	1989-1992	3.9	1	3.4	8	5.4	1320	77
7A2	1986-1988	3.1	1	3.9	6	5.5	880	61
7A3	1981-1985	2.6	1	0.9	5	4.3	590	56
7A4	1976-1980	2.6	1	1.8	6	3.3	640	56
7B1	1989-1992	3.7	2	3.1	11	5.5	1120	84
7B2	1986-1988	3.2	1	2.1	9	5.8	1010	70
7B3	1981-1985	2.8	1	0.9	5	4.7	680	50
7B4	1976-1980	2.8	1	0.9	5	4	830	65
7C1	1989-1992	3.8	2	2.7	10	5.1	1260	86
7C2	1986-1988	3	2	10.7	6	5.6	1010	73
7C3	1981-1985	2.8	1	1.2	4	3.7	870	63
7C4	1976-1980	2.7	1	1.8	6	4.1	1080	72
7D1	1989-1992	4.1	6	6.6	14	6.2	1610	105
7D2	1986-1988	3.3	2	9.3	7	6	1070	66
7D3	1981-1985	2.9	2	1.4	6	4.4	710	58
7D4	1976-1980	3	5	1.7	8	3.7	820	57
8A1	1989-1992	3.7	1	5.1	14	5.2	1390	95
8A2	1986-1988	2.9	1	1.3	19	5	840	63
8A3	1981-1985	2.7	1	1.2	5	4	590	53
8A4	1976-1980	2.6	1	1.7	5	3.7	670	52
8B1	1989-1992	3.4	2	3	16	4.8	1410	97
8B2	1986-1988	2.9	1	1.9	8	5.6	970	64
8B3	1981-1985	2.6	1	0.8	6	3.9	640	53
8B4	1976-1980	2.8	1	0.9	5	3.8	780	55
8C1	1989-1992	3.8	2	4.2	10	5.7	1760	118
8C2	1986-1988	2.8	1	2.6	7	5.3	1030	71
8C3	1981-1985	2.5	2	7	4	4.2	690	52
8C4	1976-1980	2.5	1	1.7	5	4	890	57
8D1	1989-1992	3.5	3	48.9	7	5.1	1700	96
8D2	1986-1988	3.3	1	2.5	7	5	1080	61
8D3	1981-1985	2.9	1	1.4	5	3.6	800	50
8D4	1976-1980	2.7	2	3.7	10	3.6	900	59
9A1	1989-1992	3.3	1	2.1	5	4.8	870	69
9A2	1986-1988	2.6	1	2.1	6	5.7	670	59
9A3	1981-1985	2.4	1	1.4	6	3.1	550	53
9A4	1976-1980	2.5	2	2	4	3.4	660	54
9B1	1989-1992	3.5	1	2.6	9	6.3	1230	88
9B2	1986-1988	2.7	1	1.5	7	6.4	840	61
9B3	1981-1985	2.6	1	0.8	5	4.9	650	52
9B4	1976-1980	2.6	1	1.7	6	4.9	840	57

(continued on next page)

Table A.3 (continued)

Sample ID	Sample Years	B (ppm)	Al (ppm)	Zn (ppm)	Na (ppm)	Sr (ppm)	N (ppm)	S (ppm)
9C1	1989-1992	3.4	1	3.7	11	6	1430	76
9C2	1986-1988	2.7	2	3.4	8	6.3	890	61
9C3	1981-1985	2.3	1	1.4	6	3.9	650	54
9C4	1976-1980	2.4	1	3.8	8	4.4	780	51
9D1	1989-1992	2.9	1	5.5	11	4.4	990	70
9D2	1986-1988	2.6	1	3.7	7	3.7	840	57
9D3	1981-1985	2.4	1	3.9	7	2.7	830	50
9D4	1976-1980	2.5	1	1.9	12	3.1	870	53
10A1	1989-1992	3.7	1	3	10	5.6	1150	96
10A2	1986-1988	3.4	1	2.3	9	5.7	980	75
10A3	1981-1985	3.1	1	3	5	5	710	59
10A4	1976-1980	3	1	1.3	6	4.3	600	59
10B1	1989-1992	4	1	3.3	15	5.5	1640	119
10B2	1986-1988	3.4	1	1.9	11	5.4	1070	74
10B3	1981-1985	3.2	1	1.2	9	5.1	800	61
10B4	1976-1980	2.9	1	1.4	12	4.8	800	65
10C1	1989-1992	4.4	1	4.7	13	5.6	1570	112
10C2	1986-1988	2.7	1	2.5	11	5.5	1370	78
10C3	1981-1985	3.1	1	2.6	8	4.8	920	55
10C4	1976-1980	2.7	1	21.9	5	4.4	730	55
10D1	1989-1992	3.8	1	3.8	10	5.4	1390	101
10D2	1986-1988	3.4	2	11.6	12	5.6	1140	70
10D3	1981-1985	3	1	1.4	7	4.8	810	56
10D4	1976-1980	3	1	8.9	6	4.5	820	59

Table A.4. General data for sampled red maple trees and tree-ring segments collected from control (WS7) and treatment (WS3) watersheds at Fernow Experimental Forest in 1992. WS = watershed, DBH = diameter at breast height, Width = average sample width, BAI = basal area increment.

Watershed	Tree No.	DBH (cm)	Sample Years	Sample ID	Width (mm)	BAI (cm^2)
WS7	21	12.70	1989-1992	21-1	5.15	18.05
			1986-1988	21-2	8.87	28.27
			1981-1985	21-3	25.74	51.17
WS7	22	18.03	1989-1992	22-1	8.15	44.30
			1986-1988	22-2	9.12	38.22
			1981-1985	22-3	24.51	84.36
			1976-1980	22-4	21.36	46.95
WS7	23	20.32	1989-1992	23-1	13.74	78.77
			1986-1988	23-2	10.64	55.04
			1981-1985	23-3	29.62	103.53
			1976-1980	23-4	27.08	46.43
WS7	24	17.53	1989-1992	24-1	8.72	43.06
			1986-1988	24-2	7.40	33.41
			1981-1985	24-3	21.07	76.69
			1976-1980	24-4	30.66	60.91
WS7	25	15.49	1989-1992	25-1	6.77	28.85
			1986-1988	25-2	5.90	23.13
			1981-1985	25-3	14.88	48.96
			1976-1980	25-4	20.60	43.34
WS3	26	18.03	1989-1992	26-1	9.00	45.95
			1986-1988	26-2	9.53	44.18
			1981-1985	26-3	25.95	87.39
			1976-1980	26-4	16.44	32.95
WS3	27	15.24	1989-1992	27-1	7.22	31.76
			1986-1988	27-2	6.17	24.73
			1981-1985	27-3	15.08	49.69
			1976-1980	27-4	14.55	31.97
WS3	28	13.21	1989-1992	28-1	6.57	11.00
			1986-1988	28-2	6.41	16.18
			1981-1985	28-3	15.74	43.81
			1976-1980	28-4	16.40	35.99
WS3	29	13.97	1989-1992	29-1	5.39	27.48
			1986-1988	29-2	5.53	30.76

(continued on next page)

Table A.4 (continued)

Watershed	Tree No.	DBH (cm)	Sample Years	Sample ID	Width (mm)	BAI (cm^2)
WS3	29	13.97	1981-1985	29-3	15.25	47.72
			1976-1980	29-4	17.00	21.43
WS3	30	16.51	1989-1992	30-1	4.43	41.96
			1986-1988	30-2	5.79	36.44
			1981-1985	30-3	15.98	73.79
			1976-1980	30-4	19.18	32.97

Table A.5. Tree-ring chemistry data (P, K, Ca, Mg, Mn, Fe, Cu) for red maple trees collected from control (WS7) and treatment (WS3) watersheds at Fernow Experimental Forest.

Sample ID	Sample Years	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
21-1	1989-1992	140	1080	680	70	211	5	1.3
21-2	1986-1988	80	560	710	90	208	5	0.8
21-3	1981-1985	80	540	720	130	189	6	0.9
22-1	1989-1992	160	1790	560	90	95	8	2
22-2	1986-1988	90	720	640	90	115	7	1.4
22-3	1981-1985	90	620	670	100	117	5	1
22-4	1976-1980	100	630	870	130	149	4	1
23-1	1989-1992	160	1540	630	90	143	5	1.5
23-2	1986-1988	80	610	690	80	159	3	1.1
23-3	1981-1985	70	1280	710	110	161	4	0.7
23-4	1976-1980	50	3220	750	130	139	3	0.9
24-1	1989-1992	140	1780	580	90	142	7	1.4
24-2	1986-1988	90	640	640	80	160	4	0.9
24-3	1981-1985	90	640	680	90	181	3	0.8
24-4	1976-1980	100	1340	780	120	177	6	0.8
25-1	1989-1992	140	1440	610	70	216	6	2.1
25-2	1986-1988	70	580	650	70	230	4	1.1
25-3	1981-1985	80	530	630	60	218	3	0.9
25-4	1976-1980	70	560	590	60	241	2	0.7
26-1	1989-1992	100	1050	560	70	162	5	1.3
26-2	1986-1988	80	610	600	90	168	6	1
26-3	1981-1985	80	570	630	100	174	4	0.9
26-4	1976-1980	60	490	690	80	201	5	0.8
27-1	1989-1992	110	1080	590	70	129	4	1.4
27-2	1986-1988	70	540	650	70	138	6	0.9
27-3	1981-1985	60	470	660	80	140	3	0.8
27-4	1976-1980	60	490	740	90	151	4	1

(continued on next page)

Table A.5 (continued)

Sample ID	Sample Years	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
28-1	1989-1992	100	910	610	60	227	7	1.7
28-2	1986-1988	60	510	640	60	238	6	1.8
28-3	1981-1985	60	470	670	80	247	20	1.2
28-4	1976-1980	50	490	770	90	276	7	1.2
29-1	1989-1992	100	1210	600	70	147	7	1.3
29-2	1986-1988	70	560	650	60	176	7	1
29-3	1981-1985	60	460	740	80	191	5	1.6
29-4	1976-1980	50	400	2300	130	429	5	0.9
30-1	1989-1992	100	990	570	80	181	15	1.3
30-2	1986-1988	70	490	570	80	182	11	0.9
30-3	1981-1985	70	520	590	120	198	3	1
30-4	1976-1980	60	520	650	110	219	10	0.8

Table A.6. Additional tree-ring chemistry data (B, Al, Zn, Na, Sr, N, S) for red maple trees collected from control (WS7) and treatment (WS3) watersheds at Fernow Experimental Forest.

Sample ID	Sample Years	B (ppm)	Al (ppm)	Zn (ppm)	Na (ppm)	Sr (ppm)	N (ppm)	S (ppm)
21-1	1989-1992	3.2	1	10.9	13	4	1420	109
21-2	1986-1988	2.6	1	10.9	9	3.9	950	75
21-3	1981-1985	2.6	1	9.5	8	3.7	710	70
22-1	1989-1992	2.6	1	5.8	15	3.7	1520	135
22-2	1986-1988	2.4	1	5.9	8	4.4	1120	80
22-3	1981-1985	2.3	1	4.4	7	4.3	700	67
22-4	1976-1980	2.5	1	6.5	9	5.1	720	69
23-1	1989-1992	2.8	1	5.1	25	3.1	1280	106
23-2	1986-1988	2.5	1	5.6	31	3.4	740	66
23-3	1981-1985	2.5	1	5.1	7	3.4	800	66
23-4	1976-1980	2.8	1	5.5	12	3.9	840	71
24-1	1989-1992	3	1	5.8	14	3	1390	109
24-2	1986-1988	2.7	1	4.9	11	3.4	960	73
24-3	1981-1985	2.7	1	8.8	12	3.4	840	72
24-4	1976-1980	2.9	1	10.5	9	3.6	680	78
25-1	1989-1992	3.4	1	7.8	12	3.3	1270	152
25-2	1986-1988	2.6	1	7.3	7	3.6	900	80
25-3	1981-1985	2.5	1	5.2	6	3.5	680	70
25-4	1976-1980	2.3	1	8.5	6	3.1	650	69
26-1	1989-1992	2.6	1	4.3	11	3	1190	96
26-2	1986-1988	2.5	1	3.9	10	3.1	860	68
26-3	1981-1985	2.5	1	9.1	9	3.1	630	66
26-4	1976-1980	2.5	1	5.3	9	3.4	670	59
27-1	1989-1992	2.7	1	6.9	9	3.1	1160	107
27-2	1986-1988	2.4	1	7.6	9	3.5	740	64
27-3	1981-1985	2.4	1	4.1	7	3.6	730	57
27-4	1976-1980	2.5	1	12.5	6	4.1	710	56
28-1	1989-1992	3.1	2	21.5	12	4.2	1380	122
28-2	1986-1988	2.5	1	6.4	10	4.2	1000	71
28-3	1981-1985	2.4	1	5.3	10	4.1	730	58
28-4	1976-1980	2.7	1	5.7	6	4.7	630	61
29-1	1989-1992	2.8	1	4.3	12	3.6	1130	90
29-2	1986-1988	2.7	1	8	9	3.9	820	60
29-3	1981-1985	2.6	1	5	18	4.2	770	57
29-4	1976-1980	2.7	1	5.5	7	9.4	780	70

(continued on next page)

(Table A.6 continued)

Sample ID	Sample Years	B	Al	Zn	Na	Sr	N	S
		(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
30-1	1989-1992	2.9	1	8.7	9	3.1	1100	92
30-2	1986-1988	2.3	1	2.9	6	3	710	61
30-3	1981-1985	2.4	1	3.1	12	3.1	620	51
30-4	1976-1980	2.4	1	2.8	6	3.5	520	49

Table A.7. General data for sampled yellow-poplar trees and tree-ring segments collected from control (WS7) and treatment (WS3) watersheds at Fernow Experimental Forest in 1992. WS = watershed, DBH = diameter at breast height, HTWD Year = last year of heartwood formation, Width = average sample width, BAI = basal area increment.

WS	Tree No.	DBH (cm)	HTWD Year	Sample Years	Sample ID	Width (mm)	BAI (cm^2)
WS7	11	20.07	1982	1989-1992	11-1	10.89	60.91
			1982	1986-1988	11-2	11.61	57.48
			1982	1981-1985	11-3	28.98	106.07
			1982	1976-1980	11-4	30.55	53.23
WS7	12	20.83	1984	1989-1992	12-1	10.93	62.81
			1984	1986-1988	12-2	12.89	65.53
			1984	1981-1985	12-3	34.36	123.19
			1984	1976-1980	12-4	28.51	45.82
WS7	13	20.32	1984	1989-1992	13-1	14.7	83.21
			1982	1986-1988	13-2	12.93	59.81
			1983	1981-1985	13-3	29.4	97.59
			1983	1976-1980	13-4	28.29	42.83
WS7	14	17.78	1981	1989-1992	14-1	9.78	47.23
			1982	1986-1988	14-2	12	50.62
			1981	1981-1985	14-3	18.57	59.22
			1981	1976-1980	14-4	27.87	48.08
WS7	15	20.07	1983	1989-1992	15-1	12.16	66.23
			1983	1986-1988	15-2	14.45	67.77
			1982	1981-1985	15-3	38.96	115.74
			1983	1976-1980	15-4	21.45	20.42
WS3	16	17.02	1982	1989-1992	16-1	6.77	32.35
			1982	1986-1988	16-2	5.37	23.32
			1982	1981-1985	16-3	19.14	67.77
			1982	1976-1980	16-4	32.96	65.15
WS3	17	18.29	1981	1989-1992	17-1	6.84	35.2
			1978	1986-1988	17-2	7.72	35.12
			1978	1981-1985	17-3	19.33	73.64
			1983	1976-1980	17-4	26.36	60.91
WS3	18	16.51	1982	1989-1992	18-1	2.44	11.37
			1981	1986-1988	18-2	5.41	23.48
				1981-1985	18-3	20.56	70.9
				1976-1980	18-4	16.51	53.93
WS3	19	15.75	1987	1989-1992	19-1	4.21	19.18

(continued on next page)

Table A.7 (continued)

WS	Tree No.	DBH (cm)	HTWD Year	Sample Years	Sample ID	Width (mm)	BAI (cm^2)
WS3	19	15.75	1987	1986-1988	19-2	18.08	67.31
			1987	1981-1985	19-3	33.25	70.35
WS3	20	15.75	1976	1989-1992	20-1	2.28	10.44
			1976	1986-1988	20-2	2.04	8.4
			1981	1981-1985	20-3	3.58	14.29
				1976-1980	20-4	18.47	60.2

Table A.8. Tree-ring chemistry data (P, K, Ca, Mg, Mn, Fe, Cu) for yellow-poplar trees collected from control (WS7) and treatment (WS3) watersheds at Fernow Experimental Forest.

Sample ID	Sample Years	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
11-1	1989-1992	60	940	590	90	128	5	1.9
11-2	1986-1988	30	540	610	120	161	6	1.2
11-3	1981-1985	30	480	620	120	141	3	1.4
11-4	1976-1980	10	440	700	130	140	10	1.6
12-1	1989-1992	80	1190	910	100	53	5	1.9
12-2	1986-1988	80	750	900	120	50	3	1.3
12-3	1981-1985	30	890	830	110	33	3	1.7
12-4	1976-1980	10	870	990	100	30	7	2.8
13-1	1989-1992	90	1010	700	110	122	5	1.9
13-2	1986-1988	40	600	710	130	111	2	1.1
13-3	1981-1985	30	590	700	130	105	3	1.4
13-4	1976-1980	10	490	780	140	105	4	1.8
14-1	1989-1992	100	1260	570	90	103	4	2.1
14-2	1986-1988	50	540	670	110	139	4	1.3
14-3	1981-1985	40	590	680	120	106	3	1.7
14-4	1976-1980	10	370	810	140	111	5	1.9
15-1	1989-1992	100	960	580	80	58	35	1.8
15-2	1986-1988	90	710	680	120	71	3	1.1
15-3	1981-1985	50	710	720	130	69	4	1.5
15-4	1976-1980	10	560	1010	120	72	5	3.4
16-1	1989-1992	120	2060	960	130	15	7	2
16-2	1986-1988	70	840	1050	140	20	7	1.4
16-3	1981-1985	40	480	1100	170	20	4	1.1
16-4	1976-1980	10	210	1090	120	16	6	1.3
17-1	1989-1992	170	2390	1220	160	17	7	1.5
17-2	1986-1988	50	590	1130	140	17	5	1

(continued on next page)

Table A.8 (continued)

Sample ID	Sample Years	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)
17-3	1981-1985	30	380	990	130	11	4	1
17-4	1976-1980	10	210	940	120	8	5	1.2
18-1	1989-1992	130	1290	900	140	24	17	2
18-2	1986-1988	50	600	980	140	26	8	2.1
18-3	1981-1985	30	390	900	170	25	8	1.2
18-4	1976-1980	10	150	830	130	18	7	1.3
19-1	1989-1992	100	1070	970	180	19	10	1.6
19-2	1986-1988	20	270	920	120	15	7	1.3
19-3	1981-1985	10	120	910	140	14	8	1.5
20-1	1989-1992	350	1750	980	180	12	17	2.5
20-2	1986-1988	110	1120	890	120	12	7	1.7
20-3	1981-1985	60	640	880	120	13	7	1.3
20-4	1976-1980	30	420	850	140	16	4	1.2

Table A.9. Additional tree-ring chemistry data (B, Al, Zn, Na, Sr, N, S) for yellow-poplar trees collected from control (WS7) and treatment (WS3) watersheds at Fernow Experimental Forest.

Sample ID	Sample Years	B (ppm)	Al (ppm)	Zn (ppm)	Na (ppm)	Sr (ppm)	N (ppm)	S (ppm)
11-1	1989-1992	2	6	4.4	8	4.5	1240	83
11-2	1986-1988	1.9	5	3.9	8	4.5	1150	72
11-3	1981-1985	1.8	7	4.3	6	4.7	1040	68
11-4	1976-1980	2	10	4.3	7	5.4	1020	68
12-1	1989-1992	2.2	7	2.5	8	6.2	1390	88
12-2	1986-1988	2	6	4.4	6	6.1	1870	79
12-3	1981-1985	2	7	15.4	6	5.8	1130	73
12-4	1976-1980	2.2	9	3.2	17	6	1080	77
13-1	1989-1992	1.8	7	3.5	8	4.5	1170	82
13-2	1986-1988	2	5	3.1	8	4.7	920	64
13-3	1981-1985	1.9	8	2.5	7	4.8	950	71
13-4	1976-1980	1.9	9	2.3	8	5.3	900	69
14-1	1989-1992	1.9	5	5.1	12	3.9	1210	86
14-2	1986-1988	1.8	5	4.2	6	4.3	1070	78
14-3	1981-1985	1.8	6	6.6	7	4.2	1000	76
14-4	1976-1980	1.9	8	3.2	9	5	1140	69
15-1	1989-1992	2	5	5.7	8	4	1300	96
15-2	1986-1988	1.9	4	3.1	5	4.5	1000	91
15-3	1981-1985	2	6	3.5	6	4.8	900	80
15-4	1976-1980	2.3	13	6.9	10	6.3	1280	96
16-1	1989-1992	2.4	7	3.9	10	8.2	1790	132
16-2	1986-1988	2.3	8	3.3	12	8.8	1440	104
16-3	1981-1985	2.1	8	2.1	8	9.1	1280	90
16-4	1976-1980	2.2	7	2.3	8	8.8	1010	94
17-1	1989-1992	2.3	4	3.1	10	9.6	1280	95
17-2	1986-1988	2.2	4	21.2	8	8.9	980	73
17-3	1981-1985	2.2	4	1.6	6	8	960	70
17-4	1976-1980	2.3	8	25	12	7.6	1150	84
18-1	1989-1992	2.6	10	13.8	21	8.3	1890	149
18-2	1986-1988	2.1	7	3.8	14	8.4	1250	99
18-3	1981-1985	2.1	8	3.6	8	7.8	1080	81
18-4	1976-1980	2	10	2.5	6	7.2	1050	82

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(Table A.9 continued)

Sample ID	Sample Years	B (ppm)	Al (ppm)	Zn (ppm)	Na (ppm)	Sr (ppm)	N (ppm)	S (ppm)
19-1	1989-1992	2.8	8	6.8	10	9	1420	122
19-2	1986-1988	2.2	9	8.9	7	8.2	1250	88
19-3	1981-1985	2.1	8	3.5	6	7.8	1040	78
20-1	1989-1992	2.7	11	9.3	39	7	2560	187
20-2	1986-1988	2.3	5	4.5	19	6.8	1360	122
20-3	1981-1985	2.3	5	4.6	12	7.1	1180	113
20-4	1976-1980	2	6	7.8	6	6.8	900	77

Table A.10. General characteristics of soil samples collected from control (WS7) and treatment (WS3) watersheds at Fernow Experimental Forest. Letter in Sample ID indicates soil horizon of sample. CEC = cation exchange capacity.

Watershed	Sample ID	Max. Depth (cm)	Soil pH	CEC meq/100 g
7	56A	9	4.8	13.40
7	56B	22	4.8	9.50
7	66A	6	4.6	14.80
7	66B	21	4.9	8.30
7	62A	10	4.9	13.8
7	62B	25	4.8	7
7	61A	8	6.1	13.2
7	61B	21	5.8	10
7	63A	12	5.1	13.7
7	63B	27	5	12.4
3	32A	6	4.6	6.9
3	32B	21	4.5	13.5
3	26A	3	3.9	15.1
3	26B	17	4.3	9.4
3	30A	4	4.2	13.5
3	30B	15	4.6	7
3	27A	6	4.1	18.2
3	27B	15	4.6	10.6
3	29A	5	4.2	14.7
3	29B	16	4.7	9.4
3	33A	5	4.2	16.4
3	33B	21	4.6	8.3
3	34A	7	4.4	11.2
3	34B	22	4.6	7
3	39A	6	4.1	16.9
3	39B	18	4.9	8.3
3	31A	5	4	14.5
3	31B	20	4.8	6.9
3	28A	5	4.1	13.4
3	28B	17	4.7	9.4
3	37A	6	4.4	13.3
3	37B	18	4.6	8.2
3	38A	10	4.5	11.3
3	38B	20	4.7	7
3	40A	7	4.4	14.5

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Table A.10 (continued)

Watershed	Sample ID	Max. Depth (cm)	Soil pH	CEC meq/100 g
3	40B	20	4.5	9.4
3	36A	10	4.5	13.3
3	36B	20	4.6	9.5
3	35A	5	4.3	14.5
3	35B	17	4.6	9.4
3	45A	6	4.3	17.1
3	45B	20	4.6	8.2
3	49A	3	4.2	14.7
3	49B	18	4.6	6.8
3	47A	3	4.5	13.6
3	47B	18	4.7	5.7
3	44A	6	4.4	16.9
3	44B	18	4.7	8.2
3	43A	7	3.9	22
3	43B	18	4.7	8.2
3	46A	5	4.4	10.8
3	46B	19	4.5	6.7
3	42A	4	4.4	13.4
3	42B	18	4.7	8.3
3	41A	10	4.6	15.7
3	41B	20	4.9	10
3	48A	6	4.3	12.1
3	48B	18	4.5	8.2
3	50A	8	4.4	13.4
3	50B	20	4.8	7
7	59A	6	4.5	14.7
7	59B	20	4.9	11.9
7	58A	9	4.5	16.6
7	58B	24	4.9	9.4
7	60A	10	4.9	17.7
7	60B	20	5	14.3
7	64A	5	4.6	14.2
7	64B	20	4.6	18.3
7	65A	7	4.7	17.7
7	65B	23	4.8	13.4
7	53A	6	4.3	17.1
7	53B	20	4.8	8.2
7	54A	6	4.4	14.7
7	54B	21	4.7	8.2
7	55A	3	4.5	14.6
7	55B	23	4.8	6.9
7	57A	3	4.5	15

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Table A.10 (continued)

Watershed	Sample ID	Max. Depth (cm)	Soil pH	CEC meq/100 g
7	57B	20	4.7	13.2
7	69A	6	4.7	14.9
7	69B	25	4.8	11.9
7	52A	6	4.3	13.3
7	52B	21	4.8	8.3
7	51A	11	5	11.3
7	51B	25	5	9.5
7	74A	4	4.3	15.8
7	74B	20	4.8	8.2
7	75A	3	4.4	14.8
7	75B	20	4.9	5.7
7	67A	9	5	13
7	67B	25	4.7	8.5
7	71A	4	4.5	14
7	71B	20	4.8	5.9
7	68A	11	5.2	10.8
7	68B	25	4.9	9.7
7	70A	9	4.5	16.2
7	70B	24	4.6	13.4
7	73A	5	4.4	12.50
7	73B	19	4.9	8.70
7	72A	7	4.2	17.2
7	72B	21	4.6	9.5

Table A.11. Soils data (N, P, K, Mg, Ca, Na) collected from control (WS7) and treatment (WS3) watersheds at the Fernow Experimental Forest. Letter in Sample ID indicates the horizon of the sample. WS = watershed.

WS	Sample ID	N (ppm)	P (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	Na (ppm)
7	56A	9040	16	86.02	19.55	96.24	28.8
7	56B	4000	6	46.92	19.55	48.12	26.5
7	66A	4570	19	54.74	19.55	132.33	33.4
7	66B	102	4	46.92	19.55	64.16	27.6
7	62A	3220	9.5	97.75	39.1	148.37	26.45
7	62B	1000	7	31.28	19.55	62.155	28.75
7	61A	4250	11.5	132.94	136.85	1894.725	7.59
7	61B	1440	6	74.29	136.85	1042.6	8.05
7	63A	4570	27.5	66.47	39.1	380.95	31.05
7	63B	2420	14	46.92	19.55	146.365	28.75
3	32A	880	2.5	35.19	19.55	48.12	27.6
3	32B	3930	7	66.47	19.55	126.315	31.05
3	26A	5420	10	74.29	39.1	160.4	35.65
3	26B	990	2.5	31.28	19.55	40.1	32.2
3	30A	5190	10	66.47	39.1	114.285	44.85
3	30B	940	4	35.19	19.55	68.17	34.5
3	27A	2770	9.5	62.56	19.55	80.2	33.35
3	27B	980	5	35.19	19.55	44.11	29.9
3	29A	3320	6	66.47	19.55	108.27	36.8
3	29B	1150	5	35.19	19.55	50.125	35.65
3	33A	3940	11.5	70.38	39.1	178.445	32.2
3	33B	1190	4	31.28	19.55	62.155	29.9
3	34A	2950	13.5	58.65	39.1	126.315	27.6
3	34B	800	4	27.37	19.55	60.15	31.05
3	39A	4300	6	54.74	19.55	76.19	35.65
3	39B	1290	5	43.01	19.55	66.165	36.8
3	31A	2990	8	58.65	19.55	78.195	32.2
3	31B	850	6	23.46	19.55	38.095	120.75
3	28A	3720	9.5	62.56	19.55	116.29	36.8
3	28B	1300	6	39.1	19.55	44.11	34.5
3	37A	3550	8	58.65	19.55	88.22	34.5
3	37B	1300	2.5	27.37	19.55	52.13	35.65
3	38A	3640	8	86.02	39.1	134.335	40.25
3	38B	1310	4	35.19	19.55	58.145	29.9
3	40A	5340	6	58.65	19.55	62.155	35.65
3	40B	970	2	31.28	19.55	36.09	31.05

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Table A.11 (continued)

WS	Sample ID	N (ppm)	P (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	Na (ppm)
3	36A	2890	7	58.65	19.55	80.2	35.65
3	36B	1250	2.5	27.37	19.55	58.145	6.44
3	35A	2290	6	46.92	19.55	68.17	34.5
3	35B	1090	2.5	23.46	19.55	44.11	35.65
3	45A	5750	9.5	66.47	19.55	98.245	33.35
3	45B	1090	2.5	31.28	19.55	44.11	31.05
3	49A	2790	7	54.74	19.55	102.255	39.1
3	49B	740	4	19.55	19.55	38.095	42.55
3	47A	3560	7	78.2	39.1	126.315	37.95
3	47B	890	2.5	35.19	19.55	48.12	34.5
3	44A	3120	7	54.74	19.55	76.19	37.95
3	44B	1060	2	27.37	19.55	48.12	32.2
3	43A	6060	8	46.92	19.55	118.295	24.15
3	43B	920	2.5	23.46	19.55	46.115	23
3	46A	2790	13.5	58.65	19.55	68.17	35.65
3	46B	1040	5	23.46	0	36.09	33.35
3	42A	4350	14.5	78.2	19.55	108.27	32.2
3	42B	1740	5	35.19	19.55	54.135	31.05
3	41A	8420	50.5	117.3	39.1	250.625	32.2
3	41B	1300	10	39.1	19.55	154.385	31.05
3	48A	4600	11.5	66.47	19.55	92.23	33.35
3	48B	1190	4	39.1	19.55	48.12	34.5
3	50A	4190	9.5	74.29	19.55	106.265	32.2
3	50B	880	4	35.19	19.55	58.145	26.45
7	59A	5260	32	62.56	19.55	102.255	26.45
7	59B	1960	20	27.37	19.55	66.165	28.75
7	58A	5910	34	113.39	39.1	198.495	32.2
7	58B	1630	8	39.1	19.55	46.115	27.6
7	60A	6560	26.5	148.58	58.65	619.545	25.3
7	60B	3350	14.5	82.11	39.1	258.645	32.2
7	64A	3560	16	101.66	39.1	222.555	31.05
7	64B	1390	2	66.47	19.55	104.26	37.95
7	65A	4180	24.5	74.29	39.1	194.485	29.9
7	65B	1370	14	46.92	19.55	116.29	32.2
7	53A	3700	9.5	66.47	19.55	102.255	26.45
7	53B	820	2.5	27.37	19.55	48.12	27.6
7	54A	3290	10	66.47	19.55	106.265	33.35
7	54B	790	2.5	27.37	19.55	40.1	36.8
7	55A	3720	11.5	78.2	19.55	80.2	33.35
7	55B	920	2.5	31.28	19.55	40.1	28.75
7	57A	4590	19	89.93	39.1	138.345	32.2
7	57B	2210	7	54.74	19.55	80.2	26.45

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Table A.11 (continued)

WS	Sample ID	N (ppm)	P (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	Na (ppm)
7	69A	4780	9.5	70.38	19.55	136.34	29.9
7	69B	1510	2.5	39.1	19.55	56.14	28.75
7	52A	3720	6	50.83	19.55	92.23	29.9
7	52B	1050	4	43.01	19.55	48.12	27.6
7	51A	4320	17	66.47	19.55	158.395	33.35
7	51B	1580	4	50.83	19.55	56.14	31.05
7	74A	2960	9.5	50.83	19.55	102.255	23
7	74B	1350	5	31.28	19.55	48.12	24.15
7	75A	3160	8	66.47	19.55	116.29	24.15
7	75B	870	2.5	27.37	19.55	44.11	24.15
7	67A	6370	30	86.02	58.65	453.13	35.65
7	67B	660	5	31.28	19.55	108.27	26.45
7	71A	5400	22	50.83	39.1	222.555	78.2
7	71B	770	4	35.19	19.55	72.18	28.75
7	68A	3730	10	43.01	19.55	322.805	35.65
7	68B	1740	8	31.28	19.55	104.26	26.45
7	70A	3810	19	97.75	19.55	144.36	26.45
7	70B	1780	10	78.2	39.1	74.185	33.35
7	73A	4000	12	58.65	39.10	140.35	38.0
7	73B	720	4	23.46	19.55	140.35	35.7
7	72A	4180	11.5	54.74	19.55	140.35	31.05
7	72B	1290	4	27.37	19.55	66.165	28.75

Table A.12. Additional soils data (Al, Mn, Fe, Ni, Cu, Zn, Cd, Pb) collected from control (WS7) and treatment (WS3) watersheds at the Fernow Experimental Forest. Letter in Sample ID indicates the horizon of the sample. WS = watershed.

WS	Sample ID	Al	Mn	Fe	Ni	Cu	Zn	Cd	Pb
		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
7	56A	216.0	119.0	136.0	1.00	1.50	9.00	0.30	7.50
7	56B	236.0	33.0	33.0	0.50	0.50	1.50	0.20	1.50
7	66A	202.5	147.5	186.0	1.00	1.50	5.50	0.20	20.00
7	66B	245.0	22.5	36.5	0.50	0.50	1.50	0.20	3.00
7	62A	204	178	88	1	1.5	4.5	0.2	4
7	62B	184	36.5	35	0.5	0.5	1	0.2	2
7	61A	12.7	73.4	39	1.7	1.4	26.4	0.53	4.4
7	61B	37.7	12.7	21.8	0.3	1.1	1.2	0.06	1.5
7	63A	173.5	204.5	101	2	1.5	12.5	0.4	12.5
7	63B	230.5	119	53	1	1	2.5	0.2	2.5
3	32A	268	12	46.5	0.5	0.5	1	0.2	1
3	32B	211.5	129	352	0.5	1	3.5	0.2	10
3	26A	172.5	147	456	0.5	1	5.5	0.2	10.5
3	26B	301	18.5	64.5	0.5	0.5	1.5	0.2	1.5
3	30A	177	185.5	494	1	1.5	6.5	0.2	12
3	30B	266.5	23.5	50.5	0.5	0.5	1.5	0.2	1
3	27A	225	41.5	464	0.5	0.5	4	0.2	8.5
3	27B	254	9.5	63	0.5	0.5	2	0.2	2
3	29A	210.5	58.5	359.5	0.5	1	3	0.2	12.5
3	29B	236.5	14	61.5	0.5	0.5	2.5	0.2	2.5
3	33A	122	109.5	385.5	0.5	1	4.5	0.2	11.5
3	33B	253	43	79.5	0.5	1	1.5	0.2	2.5
3	34A	90.5	93.5	487	0.5	0.5	3.5	0.2	10
3	34B	223	25	125	0.5	0.5	1	0.2	2
3	39A	193.5	34.5	470	0.5	1	2	0.2	10.5
3	39B	270.5	34.5	76	0.5	0.5	1.5	0.2	3
3	31A	228.5	49.5	400.5	0.5	0.5	2	0.2	8.5
3	31B	192	14	52	0.5	1	4	0.2	1.5
3	28A	150.5	68	476.5	0.5	0.5	15	0.2	8
3	28B	256.5	18	112.5	0.5	0.5	4.5	0.2	6.5
3	37A	190	191.5	238	0.5	1.5	6	0.2	8
3	37B	207	41	42.5	0.5	0.5	1	0.2	0.5
3	38A	172	168.5	285.5	1	1.5	5	0.2	9.5
3	38B	192	31	44.5	0.5	0.5	2.5	0.2	3.5
3	40A	224.5	231.5	199	0.5	1	2.5	0.2	5.5

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Table A.12 (continued)

WS	Sample ID	Al	Mn	Fe	Ni	Cu	Zn	Cd	Pb
		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
3	40B	212.5	38	40	0.5	0.5	1.5	0.2	2
3	36A	166	191	211	1	1.5	4.5	0.2	7
3	36B	57.2	54.2	40.2	0.3	0.2	1	0.04	0.1
3	35A	201.5	78	255	0.5	1	3	0.2	11
3	35B	234.5	38	68	0.5	1	4.5	0.2	2
3	45A	133.5	213.5	374.5	1	1.5	6.5	0.2	11
3	45B	225.5	32.5	38	0.5	0.5	1	0.2	1
3	49A	174.5	66	425.5	0.5	1	8	0.2	13
3	49B	205	8	31.5	0.5	0.5	1	0.2	2
3	47A	154.5	255	268	1	1.5	18.5	0.2	8.5
3	47B	196.5	24	37.5	0.5	0.5	2	0.2	2
3	44A	198.5	126	311	0.5	1.5	5	0.2	7
3	44B	254.5	17	37.5	0.5	0.5	1	0.2	1.5
3	43A	170.5	59.5	463	0.5	2	16	0.2	12.5
3	43B	239.5	14	49.5	0.5	0.5	3	0.2	3.5
3	46A	226.5	133.5	226.5	0.5	2	20	0.2	23.5
3	46B	209.5	16	34	0.5	1	6	0.2	1
3	42A	227	213	285	1	1.5	6.5	0.2	9.5
3	42B	251.5	37.5	46.5	0.5	1	2	0.2	1
3	41A	176.5	448.5	226	2.5	2.5	37.5	0.45	7.5
3	41B	242	58	54.5	0.5	1	2.5	0.2	1.5
3	48A	218	230	199.5	0.5	1.5	2.5	0.2	7
3	48B	220.5	30.5	38	0.5	0.5	1	0.2	1.5
3	50A	185.5	159	405	0.5	1.5	7	0.2	38
3	50B	233	20	35.5	0.5	0.5	1	0.2	1.5
7	59A	187.5	159	196.5	0.5	1.5	7.5	0.2	9
7	59B	247.5	52	52.5	0.5	0.5	2.5	0.2	4
7	58A	147	158	366.5	1	1.5	8.5	0.2	13
7	58B	257	30	42	0.5	0.5	1	0.2	2.5
7	60A	155	228	187	2	2.5	23	0.6	7.5
7	60B	229	82	79.5	1	1	6.5	0.2	2.5
7	64A	253	134	129	0.5	1.5	6	0.2	9.5
7	64B	352.5	41.5	76.5	0.5	0.5	4	0.2	1
7	65A	226	571.5	94	2	3.5	10.5	0.4	4.5
7	65B	242	167	37	1	1	5	0.2	1.5
7	53A	169	59	369	0.5	0.5	3.5	0.2	9.5
7	53B	240.5	20	36.5	0.5	0.5	1	0.2	3
7	54A	195	160.5	260.5	1	1.5	6	0.2	8
7	54B	253	34	53	0.5	1	2	0.45	3.5
7	55A	175.5	175	217.5	0.5	1.5	20.5	0.2	7
7	55B	198.5	31.5	37	0.5	0.5	0.5	0.2	1.5
7	57A	154	185.5	236	0.5	2	10.5	0.2	12.5

(continued on next page)

Table A.12 (continued)

WS	Sample ID	Al	Mn	Fe	Ni	Cu	Zn	Cd	Pb
		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
7	57B	244.5	71.5	130	0.5	1	4	0.2	4
7	69A	205	195	200	1	2	8.5	0.3	5.5
7	69B	242	33.5	51	0.5	0.5	1.5	0.2	1.5
7	52A	135	136	287	0.5	2.5	7	0.2	11
7	52B	209	52.5	36	0.5	1.5	1.5	0.2	4
7	51A	239.5	128.5	63	8	2	7	0.2	6
7	51B	197.5	58.5	41.5	0.5	0.5	1	0.2	0.5
7	74A	157.5	65	368	0.5	1	3	0.2	11.5
7	74B	222	18.5	53	0.5	0.5	1	0.2	3.5
7	75A	155.5	69	357.5	0.5	1	5.5	0.2	13
7	75B	198	13	29.5	0.5	0.5	1	0.2	4
7	67A	117	294.5	284.5	1.5	2.5	23.5	0.5	23
7	67B	206	32	41.5	0.5	0.5	0.5	0.2	3
7	71A	120.5	307.5	347	1.5	3	3	0.25	6
7	71B	218.5	39.5	79	0.5	1	0.5	0.2	1.5
7	68A	155	247.5	71	2	1.5	10	0.2	3.5
7	68B	172.5	68	143.5	0.5	0.5	1.5	0.2	2
7	70A	173.5	167	217.5	8	2.5	5.5	0.2	4.5
7	70B	261	79.5	89	0.5	1	2	0.3	1.5
7	73A	149.0	122.0	293.5	0.50	1.50	0.50	0.20	7.50
7	73B	259.5	48.0	70.5	0.50	0.50	0.50	0.20	0.50
7	72A	150	64	501.5	1	1.5	0.5	0.2	10
7	72B	285	21	96	0.5	1	0.5	0.2	1