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Correlation Analysis of Tree Growth, Climate, and Acid Deposition in the Lake States

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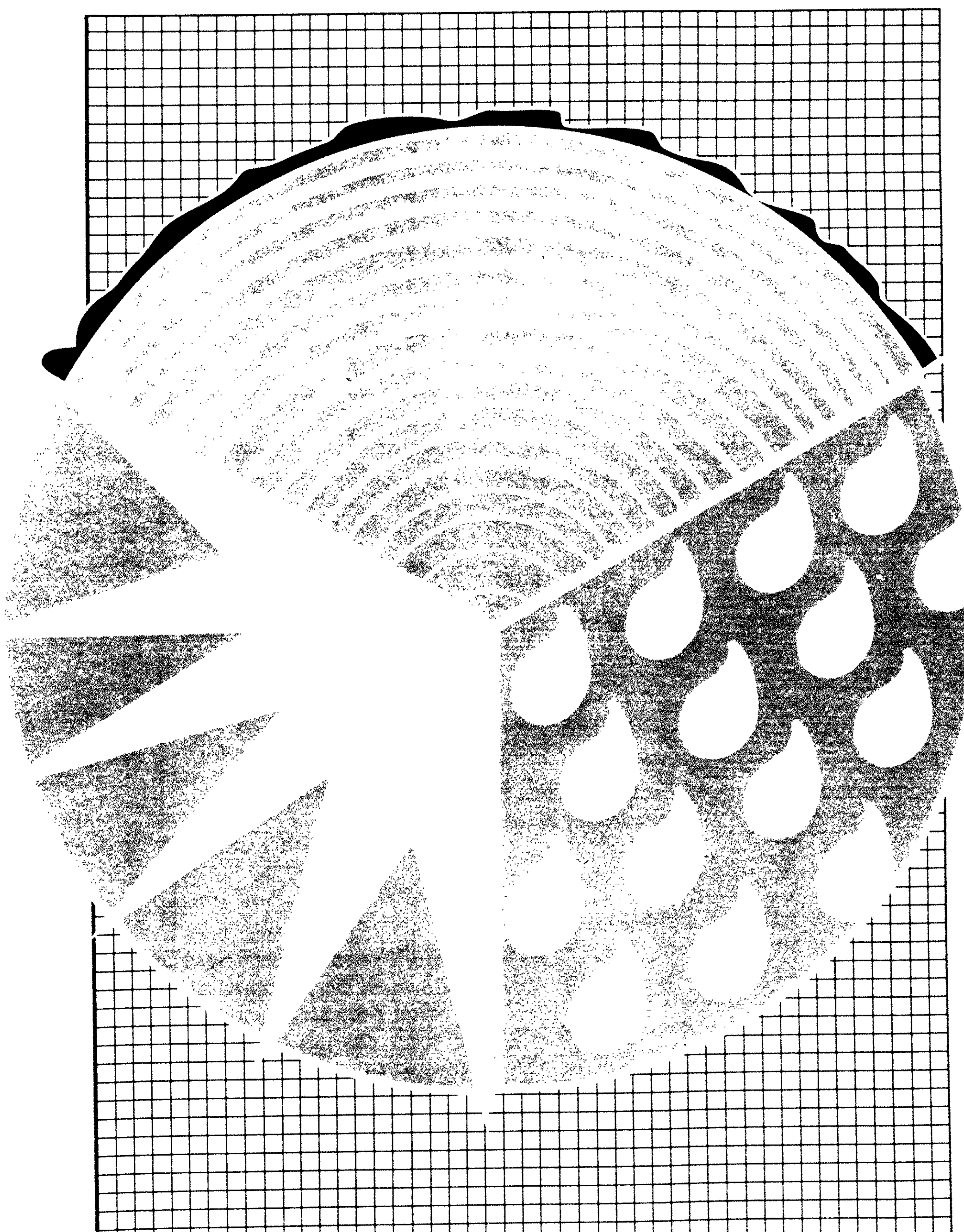

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Describes research designed to detect subtle regional tree growth trends related to sulfate (SO_4) deposition in the Lake States. Correlation methods were used to analyze climatic and SO_4 deposition. Effects of SO_4 deposition are greater on climatically stressed trees, especially pine species on dry sites, than on unstressed trees. Jack pine growth shows the strongest correlation to both climate and acid deposition.

KEY WORDS: Forest decline, growth models, sulfate deposition, environmental influences.

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Correlation Analysis of Tree Growth, Climate, and Acid Deposition in the Lake States

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Acid deposition has been suggested as a factor affecting tree growth in susceptible tree species. A study[1] was conducted to detect subtle regional trends related to sulfate (SO_4) deposition in the Lake States (Minnesota, Wisconsin, and Michigan) along a gradient of increasing SO_4 deposition from northwest to southeast. Widespread forest damage or decline is not yet evident in this area. Because climate plays an integral role in regional tree growth patterns, research was also designed to determine first the climatic effects alone and then the interaction of climate and SO_4 deposition. The effects of increasing stand and tree maturation, competition, and other site influences on tree growth were estimated by using a tree growth model.

We conducted a study to identify the macroclimatic and SO_4 deposition variables and their interactions that correlate significantly with differences in tree diameter growth in the Lake States. First we used a tree growth model, STEMS, to analyze the effects of climatic variables that significantly influence tree growth prediction errors. Then we analyzed the remaining variation in tree growth errors for correlation with patterns of SO_4 deposition.

BACKGROUND

Regional air pollution effects on forest tree growth are more subtle over large areas than the dramatic effects caused near strong local point sources. Although the effects of regional air pollution are difficult to detect, they may be cumulative and potentially damaging to entire forest areas.

The process of forest decline due to regional air pollution is very difficult to document. Air pollution stresses sensitive trees; the weakened trees lose their resistance to natural events such as insect attack, frost, and drought. When the level of stress becomes limiting, growth begins to decline. At this stage, no other visible signs of damage may be evident. This "hidden injury" from low-level, long-term exposure to air pollutants is hard to verify from field observations. The changes are extremely difficult to separate from other factors that influence growth (tree community dynamics, age, competition, moisture, temperature stress, insects, and biotic pathogens). The relationships among these factors are complex. Major growth reductions can easily be determined, but the subtle reductions in tree growth related to regional air pollution are more difficult to detect.

The stress imposed by regional pollutants may reduce growth in the more susceptible forest species. In the Eastern United States, red spruce, balsam fir, paper birch, eastern white pine, and other pines have all shown growth declines in areas of high damage (Postel 1984). In general, conifers have been more seriously damaged than hardwoods (Steinbeck 1984). This

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[1]*One of three related studies undertaken to examine relations between sulfate (SO_4) deposition and soils; SO_4 deposition and the chemical content of woody tissues (Ohmann* et al. *1987); and tree growth, climate, and SO_4 deposition (Holdaway 1988, Shifley 1988).* *Partial funding was provided by the National Vegetation Survey Research Program under the National Acid Precipitation Assessment Program.*

may be because conifers retain foliage perennially or because most of the trees in high-risk areas have been conifers. Also, older trees seem to be more susceptible to stress than younger trees.

Acid deposition effects on tree growth cannot be evaluated without first accounting for the influence of climate on tree growth. The more humid regions lack an obvious growth limiting factor such as the long droughts that occur in relatively dry regions. In the northern areas where precipitation is normally adequate, low temperature may be the factor most limiting to tree growth. Seasonal or monthly precipitation or temperature patterns are often more important in explaining variations in tree diameter growth than annual values. Studies (*e.g.*, Coile 1936, Tryon *et al.* 1957) have shown that different climatic measures significantly influence growth, depending on the species, the variables examined, their range of values, the manner in which they are expressed (climatic indices), and the region over which they are studied.

Tree growth may also be affected by air pollution and/or by interactions between the climatic factors and chemical pollution. Variations in observed tree growth trends may be due only to climatic effects, such as heat stress and drought; acid deposition may also be a contributing factor. Climatic changes may intensify or modify already existing pollution effects.

Two factors aid in this large-scale study of the effects of acid deposition on the Lake States forests:

First, the region is overlaid with a regular well-defined wet SO_4 deposition gradient[2] that ranges from 5 kg/ha/yr in northwestern Minnesota to 30 kg/ha/yr in southeastern Michigan. In the continental U.S. wet SO_4 deposition peaks in West Virginia at 43 kg/ha/yr (Harris and Verry 1985). Thus, the Lake States region includes the lower and middle ranges of the deposition gradient in the United States. It is a borderline area where more subtle regional tree growth trends may be evident.

Second, a Lake States individual-tree growth model, STEMS/TWIGS, is available (Belcher *et al.* 1982, Holdaway and Brand 1986). Analysis of tree growth for relationships with climatic and acid deposition factors is difficult owing to the large variability in tree growth patterns due to stand, tree, and site effects. Also, as stands mature and increase in density, the natural physiological processes cause a normal decline in tree growth (Hyink and Zedaker 1987). We must account for this natural stand evolution before we can determine if an apparent forest decline is truly anomalous. Stand dynamics can be estimated using a tree growth model, such as Lake States STEMS/TWIGS. The biologically based growth and mortality models in STEMS attempt to quantify the complex ecological processes involved in tree and stand development. The empirical data base used to calibrate STEMS was extensive enough to allow for complex, nonlinear model forms. The predictions provide an average condition against which to evaluate the degree to which forest growth has departed from "normality." Deviations from growth predicted by the model can be attributed to factors such as the macroclimate and SO_4 deposition that are not explicitly modeled in STEMS. Other unaccounted for sources of variation in STEMS residuals included soil type, soil moisture class, topography, other more localized climatic variations, anthropogenic disturbance, and the interaction of these factors.

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[2]Sulfate, nitrate, and acid precipitation all show fairly similar distributions of their respective gradients (Seilkop and Finkelstein 1987). Although sulfate deposition is the focus of this paper, any conclusion drawn should apply equally well to all forms of atmospheric pollution mentioned.

STUDY AREA

The study was confined to forest land systematically sampled across all of Wisconsin, all of Michigan except for three National Forests, and the Chippewa National Forest and the Cloquet Experimental Forest in northern Minnesota (fig. 1). Most forests in these States are relatively young, having been extensively cut over near the turn of the century. The climate of the two Minnesota study areas and Wisconsin are typically continental. Most of Michigan has a quasi-marine climate due to the Great Lakes. Average annual temperature for the study area ranges from 37 to 50°F, and total annual precipitation ranges from 24 to 40 inches.

Minnesota

The Chippewa National Forest is located in north-central Minnesota. Retreating glaciers left a landscape of flat to gently rolling terrain that is interrupted by areas of low hills and numerous wetlands. The vegetation of the forest reflects the forest's position near the boundaries of three major vegetative communities—the coniferous forest to the north, the hardwood forest to the south, and the prairie to the west.

Data available from the University of Minnesota's Cloquet Experimental Forest in northeastern Minnesota were included in the study to strengthen the data base in northern Minnesota.

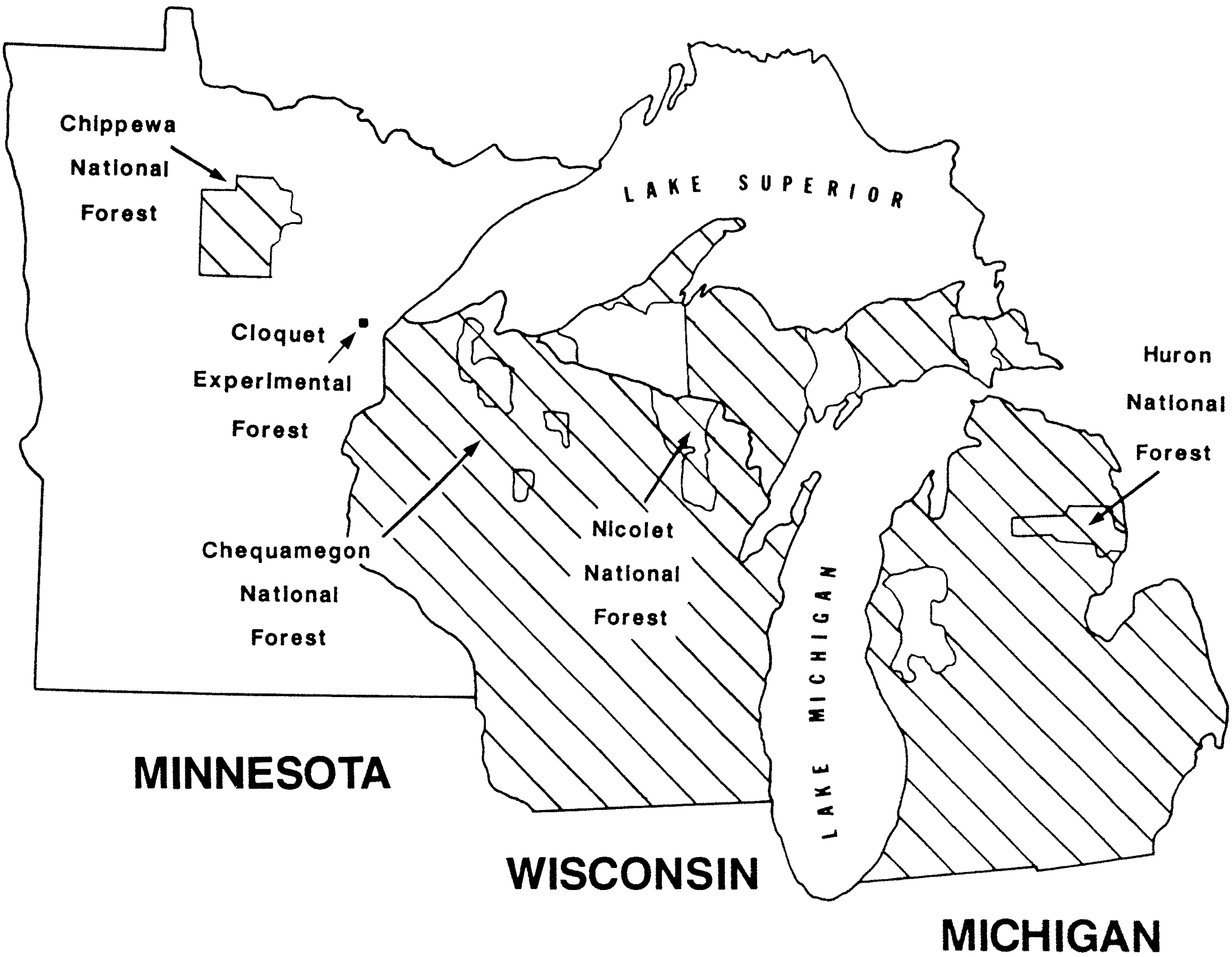

Figure 1.—*Shaded areas represent location of data sources in Minnesota, Wisconsin, and Michigan. Four areas in Michigan, representing three National Forests, were not sampled.*

The Experimental Forest lies on a glacial outwash plain containing scattered low ridges, knolls, and bogs. Upland vegetation types occur in two-thirds of the Experimental Forest; lowland types occur in the remainder.

Wisconsin

Except in the southwestern corner, glaciation has profoundly affected Wisconsin's physiography. A plateau extends across northern Wisconsin. Lake Michigan and Lake Superior modify the weather conditions of adjacent areas, depending on the relative temperatures of the water and the adjacent land surfaces. In the summer lake effects tend to reduce high temperatures; in the winter they tend to raise low temperatures. During spring and fall the lakes modify temperature extremes (Changnon and Jones 1972).

Michigan

Michigan is composed of two large peninsulas jutting into one of the world's largest bodies of fresh water. The Great Lakes and variations in elevation are important in determining Michigan's climate. Modified temperature patterns similar to those in Wisconsin are found adjacent to the Great Lakes. Because the lakes respond slowly to temperature changes, both summer and winter arrive there later than in Minnesota and Wisconsin. The lakes also cause precipitation patterns to differ locally; areas downwind of the lakes receive relatively more precipitation in the fall and winter than in the spring and summer. Roughly half of the State is covered by level terrain or gently rolling hills. However, the western half of the Upper Peninsula and the northern half of the Lower Peninsula contain elevated tablelands.

GROWTH DATA

Continuous Forest Inventory (CFI) remeasurement data were obtained from the surveys conducted by the North Central Forest Experiment Station, USDA Forest Service. All non-National Forest forested areas were systematically sampled in a survey of two of the States (Wisconsin and Michigan). Four National Forests (one in Minnesota, two in Wisconsin, and one in Michigan) were also systematically sampled. This CFI data represents the largest data base available in the region. This data base consists of detailed plot and tree measurements and history transcribed onto carefully edited data tapes. Added to this were data from the University of Minnesota's Experimental Forest plots at Cloquet, Minnesota (table 1). Together, the two sources include 2,408 plots.

Table 1.—*Distribution of remeasurement plots used in the data analysis along with number of plots (disturbed plots removed) and measurement years*

Area	Number of plots	Dates of measurement	
		Initial	Final
Minnesota			
Chippewa National Forest	77	1969	1979
Cloquet Experimental Forest	199	1977	1983
Wisconsin			
State Survey[1]	1,291	1967-69	1981-83
Chequamegon National Forest	100	1975	1981-83
Nicolet National Forest	126	1974	1982
Michigan			
State Survey[1]	520	1964-66	1978-81
Huron National Forest	95	1977	1982-83
	2,408		

[1]State Surveys were conducted by the Forest Inventory and Analysis Unit, North Central Forest Experiment Station, St. Paul, MN, on non-National Forest lands only.

Seventy percent of the plots had remeasurement intervals of 13 to 15 years; the range was 6 to 16 years.

The State survey and National Forest plots were variable-radius plots, each consisting of 10 points uniformly spaced over an acre. At each point, trees ≥ 5.0 inches d.b.h. were sampled with a 37.5 factor prism. At the first three points, data from tree saplings (d.b.h. 1.0 to 4.9 inches) were recorded for 1/300-acre subplots. The Cloquet plots were 1/7-acre fixed-radius plots, and only measurements of trees with diameters greater than 4.9 inches were recorded.

The following data were recorded for each plot: plot site index, tree d.b.h., species, status (live, cut, dead), and live crown ratio. For all State survey and National Forest plots, moisture class, crown class, and plot history were also recorded. Field methods and coding criteria for these plots are described in Doman *et al.* (1981).

The STEMS model (Belcher *et al.* 1982) was used to obtain growth projections on all plots. Major effects from human causes (cutting) and natural causes (insects, disease) were excluded by eliminating plots with a history of disturbance and at least a 10-percent decrease in stand basal area.

To avoid confounding topographic relationships with macroclimatic factors, the plots were screened to select only those on sites of the most common moisture classes for each forest type (fig. 2). For the pines, only plots in moderately dry and well-drained sites were used; for black spruce, tamarack, and northern white-cedar, only plots occurring on moderately wet and very moist sites were retained. All other species were on well-drained and moderately moist sites except for oak-hickory plots on moderately dry sites.

To minimize the influence of crown position on growth patterns, only dominant, codominant, and intermediate trees were included in the data base. Scattergraphs of the average prediction errors on d.b.h. classes indicated that prediction errors for open-grown and suppressed trees are distinctly different from those for dominant and codominant trees. Data from intermediate trees, in a transition class between the two groups, were retained. These results suggest that the macroclimate has a more direct influence on overstory trees than on understory trees, which may be responding to the microclimate or to competition. Use of larger trees also concentrates attention on those trees in a stand that may be more exposed to climatic and pollution stresses than the younger understory trees. Pollution-caused declines generally affect the taller, more mature trees (Woodwell 1970).

A total of 31,700 dominant, codominant, and intermediate trees was found on plots of frequently occurring moisture classes. Each plot and the trees on that plot were assigned to the nearest weather station for estimates of climatic factors. For each species a single average residual value (*i.e.*, the difference between observed

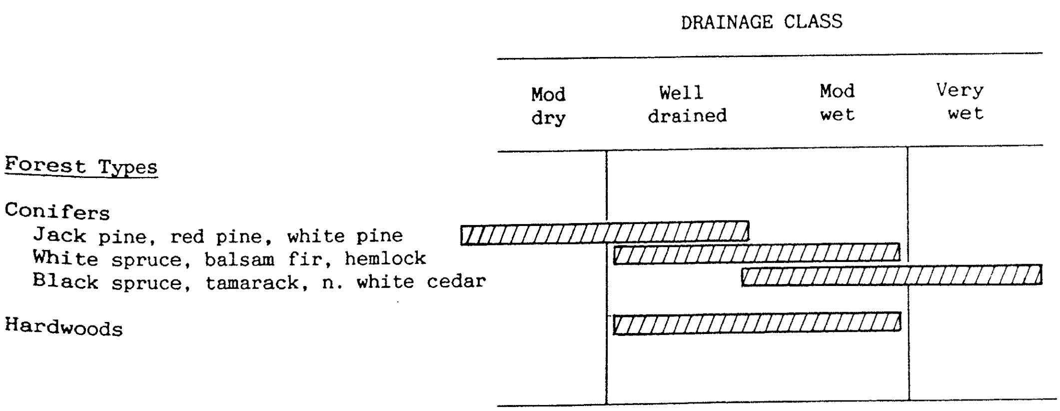

Figure 2.—*Soil drainage classes used in the study by forest type.*

diameter growth and the STEMS model estimate of that value) for all trees assigned to each weather station was used instead of plot or tree values because corresponding estimates of climatic variables at the plot were not calculated.

CLIMATIC DATA

The climatic data were obtained from yearly "Summary of Month" data tapes from the National Oceanic and Atmospheric Administration Network of Climatic Data Acquisition Stations (NOAA 1986). The most complete long-term records were available for nine climatic elements: total precipitation, mean temperature, two measures of precipitation intensity, snowfall, maximum and minimum temperatures, and two measures of temperature severity. Therefore, the selection of variables to be used was restricted to certain expressions of these nine elements. Factors such as heating and cooling days, evaporation measures, and freeze data were not included due to the incompleteness of such records rather than failure to recognize their possible importance. Even for the nine elements used, values were frequently missing from the data tapes. Stations with more than 7.5 percent of these observations missing were deleted—leaving 270 stations out of 395. Nearly half of the stations included had no more than 1 percent missing values. Missing values were estimated by using 24- or 30-year average values from the closest station from among 99 main stations (NOAA 1982).

The following climatic measurements were selected as candidates for the analysis: average minimum, mean, and maximum temperatures; total and proportional precipitation; snowfall; temperature range (average maximum July temperature minus average minimum January temperature); number of days precipitation ≥ 0.1 inch; number of days precipitation ≥ 0.5 inch; number of days minimum temperature < 0°F; and number of days maximum temperature ≥ 90°F. The more common variables were summarized by month and seasonal values; all the rest were reduced to seasonal values (table 2). Meteorological winter includes December through February; spring, March through May; summer, June through August; and fall, September through November.

These variables were selected because they were readily available and of high quality and because

Table 2.—*Monthly and seasonal climatic variables used in preliminary analysis of tree diameter growth patterns in the Lake States*

Variable description	Monthly	Seasonal	Annual	Number of variables
Temperature				
Mean temperature	X	X	X	17
Mean maximum temperature		X	X	5
Mean minimum temperature		X	X	5
Range			X	1
Number of days ≤ 0°F		X	X	5
Number of days ≥ 90°F		X	X	5
Percipitation				
Total	X	X	X	17
Proportional (Total/Annual)	X	X		16
Snowfall	X		X	13
Number of days ≥ 0.1 inch		X	X	5
Number of days ≥ 0.5 inch		X	X	5
				94

the intensity and distribution of precipitation had to be taken into account. Also, the distribution of precipitation throughout the year may be a better measure of precipitation effectiveness than the amount of precipitation.

Forest growth and climate were linked by assigning each of the remeasured inventory plots to the closest weather station. Plots in the same locality were usually measured in the same year. The climatic data for each station in the study were averaged over the remeasurement interval of the plots assigned to the station. On the average, plots were 22 km from the nearest weather station. Of the original 270 stations, 182 had plots assigned to them (fig. 3). The figure demonstrates that the monitoring stations available for analysis are irregularly spaced, with heavier sampling densities in the more populated areas. Because of low station density in the heavily forested northern areas a higher number of plots at greater distances were assigned to each station there.

SULFATE DEPOSITION DATA

Shifley (1988) described a model to predict site-specific SO_4 concentration in the Lake States. Data from 34 monitoring stations in the Lake States and bordering areas, beginning in 1979, were available. Annual SO_4 concentration at each weather station in the study was estimated by a linear function of latitude, longitude, and year (from 1979 to 1985):

$$\text{SO}_4\hat{}\text{CONC} = 16.52 - 0.1313\,(\text{YEAR} - 82.7) - 0.1862\,\text{LAT} - 0.0677\,\text{LONG}. \qquad [1]$$

Sulfate concentrations were estimated for 1983. Using the 1983 data corresponds to estimating the SO_4 concentration near the end of the remeasurement interval. The model indicates that SO_4 concentrations decreased from 1979 to 1985, but a constant proportional gradient was maintained across the Lake States. Thus, relative SO_4 concentration for the remeasurement interval is found by using the 1983 values.

Wet SO_4 deposition at each weather station was estimated as the product of the SO_4 concentrations as estimated by the model [1] and the average annual precipitation. Average annual precipitation was calculated for the measurement interval of the plots assigned to the weather station. Estimated wet SO_4 deposition at the weather stations in the study ranged from 11 kg/ha/yr in north-central Minnesota to about 35 kg/ha/yr in central lower Michigan.

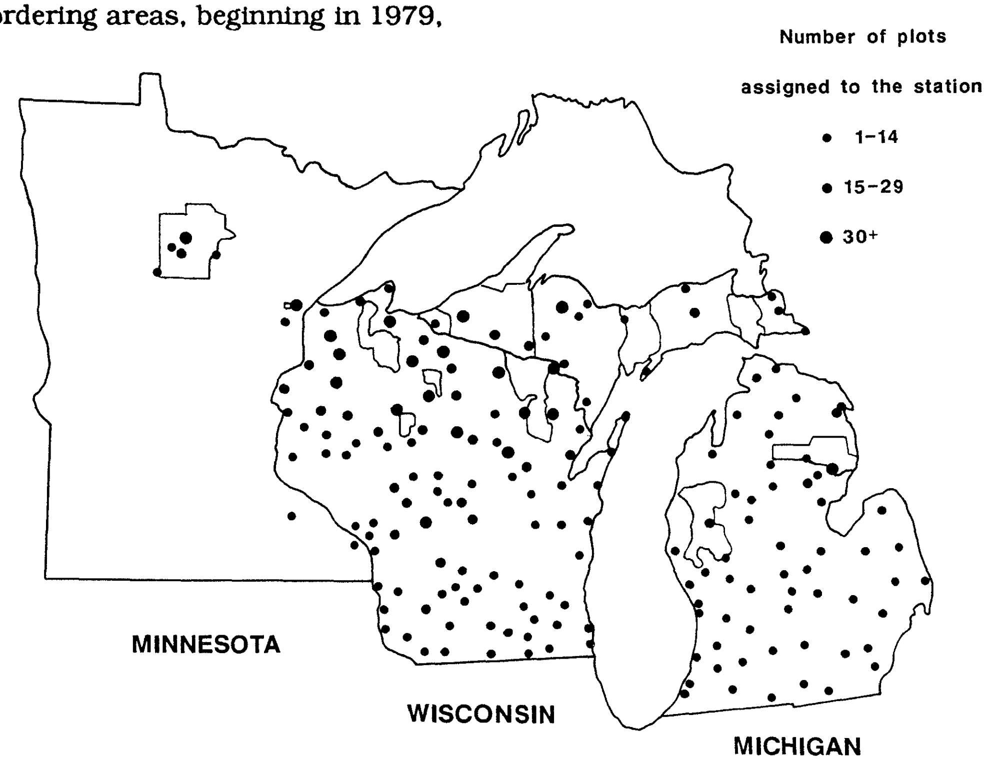

Figure 3.—*Location of weather stations used in the study of climate and SO_4 deposition on tree diameter growth in the Lake States. Study plots were assigned to the nearest weather station.*

STATISTICAL ANALYSIS

Climate

Preliminary data analyses were run to reduce the large number of potential independent variables and to limit multicollinearity between the variables. The final predictor variables were chosen according to the following criteria:

* show higher correlation with tree diameter growth prediction residuals
* show relatively low correlations with other climatic variables in the variable pool
* show similar trends over a number of tree species to eliminate random phenomena having no biological basis.

The more complex climatic indices were not included. Many of these are simply manipulations of the basic climatic data and thus are either highly correlated with the original variables or, as with the length of growing season, are closely related to the temperature or precipitation regimes.

Each tree species with more than 250 tree growth observations was analyzed separately. (Many of the more prevalent species had 1,000 to 3,500 growth observations.) The dependent variable was the average annual diameter growth prediction error (*i.e.*, the observed growth minus the STEMS model's prediction of that value) by climatic station and tree species over the measurement interval. The independent variables were the 94 initial climatic variables averaged over the measurement interval. A simple correlation analysis between the growth errors and the climatic variables was performed for each of 22 species. Based on the correlations, two grouping methods were used to condense the climatic variables to only the most important influences.

First, species were grouped by their common response to climate. An analysis of the correlations between growth prediction errors and the climatic variables showed differences between species in magnitude and direction of the correlations. The species fell into three natural groups—one conifer and two hardwood groups—distinguished primarily by their response to winter temperatures. The behavior of conifers was similar but not identical to that of the cold weather hardwoods—species often found growing with the conifers. The warm weather hardwoods showed the weakest climatic sensitivity. The three groups are:

GROUP I (Conifers)
jack pine, red pine, eastern white pine, white spruce, balsam fir, black spruce, tamarack, northern white-cedar, and hemlock.

GROUP II (Cold weather hardwoods)
basswood, sugar maple, bigtooth aspen, quaking aspen, and paper birch.

GROUP III (Warm weather hardwoods)
black ash, red maple, elm, yellow birch, white ash, white oak, northern red oak, and northern pin oak.

The analysis will focus on relationships consistent across a number of species in each climatic group to highlight the strongest climatic trends.

Second, interrelated climatic variables were grouped, and only the single variable most strongly correlated with tree growth errors was selected. Thus, for the common temperature and precipitation variables (with monthly and seasonal values), each season and the months within it were considered a group. Only one variable (a single month or the season) most strongly correlated to tree diameter growth errors was used. Also, only the higher variable of either total or proportional precipitation for each group was used. For the four "No. of days" variables (summarized by seasonal values only), the single strongest seasonal or annual variable was used. Snowfall showed monthly correlation trends but no seasonal trends; thus, it was represented by the single strongest monthly variable. When two variables in a group were highly correlated with the d.b.h. growth errors, as well as with each other, the one least correlated with the remaining independent variable pool was used. Because of high correlations (> 0.90) between spring and summer temperatures and fall and winter temperatures (for maximum, mean, and minimum values), two new variables were created using the average cold season (fall + winter) temperatures and the average warm season (spring + summer) temperatures. This composite variable or the strongest monthly variable from which it was composed was retained in the analysis.

Average correlations for each climatic variable across all species in a species group were calculated. Species correlation coefficients included in the average had to be:

* significant at $P = 0.001$ to help compensate for the auto-correlation present in spatial studies
* of the same sign
* ≥ 0.2 in absolute value.

Eliminating the weaker correlations avoided masking stronger trends. Based on the average correlation coefficients, only the strongest climatic variable from within groups of interrelated independent variables was retained. The final selection of the main variables was performed separately for the conifers and for the two hardwood groups.

A procedure similar to that used to screen single climatic variables was used to test for the strongest temperature x precipitation interactions. All possible monthly and seasonal interaction combinations were tested, and only the strongest for each seasonal group was retained. The cross product was tested as well as measures of precipitation effectiveness such as the ratio of precipitation and temperature.

Stepwise multiple regressions were run on each species using the final single climatic and climatic interaction variables (SPSS Inc. 1986). Independent variables were removed if P was $>$ 0.01, and they were entered if P was $<$ 0.001. Snowfall was eliminated due to its relatively low correlation with tree diameter growth and because of its high correlation with average minimum cold season temperature (-0.88).

SO_4 Deposition

Similar rules were used to evaluate relationships between tree diameter growth and SO_4 deposition x climate interactions for the three species groups. The primary climatic variables used were the four climatic interactions of temperature and precipitation. All final climatic interactions were expressed in a form that emphasized their stressful nature. (For example, "high precipitation and low temperature in July are beneficial" became" low precipitation and high temperature in July are stressful.") Also included were the appropriate single July or June precipitation variable. These variables were used to test the significance of the SO_4 deposition x climate interaction. The relationship between tree diameter growth and SO_4 deposition alone was also analyzed. A second series of multiple linear stepwise regressions was run to evaluate the significance of SO_4 deposition x climate interaction and SO_4 deposition terms in explaining differences between observed and predicted tree diameter growth rates.

RESULTS AND DISCUSSION

Climate

Based on the criteria previously described, a set of final tree diameter growth predictor variables was selected for each of the three tree species groups. The variables chosen, including simple statistics and their correlations with tree diameter growth errors, are given in Appendices A and B. The main climatic variables related to tree growth are listed by decreasing magnitude of average correlations (table 3).

Conifers

The strongest influences of single climatic variables beneficial[3] to tree diameter growth include:

* cold falls and winters
* high number of days with intense precipitation ($\geq$ 0.5 inch) and a higher proportion of rainfall in the fall
* lower proportion of the total precipitation in December
* higher amounts of precipitation in July.

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[3]*It is more accurate to say that the climatic variables are well correlated with positive tree diameter growth errors. "Beneficial effects" implies a more direct cause and effect that is not proven by correlations with growth projection errors. However, if STEMS/TWIGS models the true condition fairly accurately and no other major factors are missing, we may assume that the climatic variables are reasonable indicators of influences.*

Table 3.—*Average correlation coefficients between STEMS/TWIGS tree growth errors and variables (P = 0.001) for all species in a group listed in descending magnitude. A positive sign indicates a positive relationship with tree growth, and a negative sign indicates a negative relationship.*

Independent variable	Average correlation coefficient	Number of species in average
GROUP I (Conifers)[1]		
Single Climatic Variables		
Number of days temp ≤ 0 F fall	+ 0.450	4
Number of days prec ≥ 0.5 inch fall	+ 0.420	4
Max temp cold season	- 0.406	5
Proportion prec December	- 0.373	4
Total prec July	+ 0.367	6
Range	+ 0.367	4
Proportion prec fall	+ 0.353	3
Number of days prec ≥ 0.1 inch summer	+ 0.322	5
Proportion prec March	+ 0.310	4
Min temp warm season	- 0.310	3
Snowfall in April or November	+ 0.290	3
Climatic Interactions		
High temp with low prec July	- 0.364	7
High prec with high temp December	- 0.352	4
High prec with low temp fall	+ 0.348	5
High prec with low temp March	+ 0.342	5
Interactions of SO_4 Deposition with Stressful Climate		
DEP1: High dep with high temp & low prec fall	- 0.410	5
DEP2: High dep with high temp & low prec March	- 0.388	6
DEP3: High dep with low prec July	- 0.347	6
DEP4: High dep with high temp & low prec July	- 0.325	6
DEP5: High dep with high prec & high temp Dec	- 0.290	4
SO_4 Deposition		
DEP: Deposition	- 0.313	3
GROUP II (Cold weather hardwoods)[2]		
Single Climatic Variables		
Total prec June	+ 0.400	4
Proportion prec fall	- 0.373	4
Number of days ≤ 0°F winter	+ 0.370	3
Min temp winter	- 0.357	3
Number of days prec ≥ 0.5 inch summer	+ 0.353	4
Range	+ 0.350	3
Proportion prec December	- 0.313	3
Snowfall September	- 0.305	2
Number of days prec ≥ 0.1 inch summer	+ 0.258	5
Proportion prec March	- 0.253	3

(Table 3 continued on next page)

(Table 3 continued)

Independent variable	Average correlation coefficient	Number of species in average
Climatic Interactions		
High temp with low prec June	- 0.356	5
High temp with high prec winter	- 0.330	3
High temp with high prec November	- 0.295	4
Interaction of SO_4 Deposition with Stressful Climate		
DEP6: Dep with low prec June	- 0.330	4
DEP7: High temp with low prec June	- 0.320	4
DEP8: High temp with high prec winter	- 0.310	3
DEP9: Dep with high temp with high prec November	- 0.277	3
SO_4 Deposition		
DEP: Deposition	- 0.300	2
GROUP III (Warm weather hardwoods)[3]		
Single Climatic Variables		
Max temp cold season	+ 0.425	2
Total prec spring	+ 0.380	3
Mean temp warm season	+ 0.370	4
Number of days temp ≤ 0°F fall	- 0.350	2
Number of days temp ≥ 0.90°F fall	+ 0.327	3
Total prec December	+ 0.320	2
Number of days prec ≥ 0.5 inch spring	+ 0.317	3
Number of days prec ≥ 0.1 inch spring	+ 0.310	2
Proportion prec fall	- 0.283	3
Climatic Interactions		
High prec with high temp spring	+ 0.375	4
High prec with high temp winter	+ 0.365	2
Interactions of SO_4 Deposition with Stressful Climate		
DEP10: Dep with low prec and low temp spring	- 0.295	2
DEP11: Dep with low prec and low temp winter	- 0.285	2
SO_4 Deposition		
DEP: Deposition	+ 0.380	2

[1]Jack pine, red pine, white pine, white spruce, balsam fir, black spruce, tamarack, northern white-cedar, and hemlock.
[2]Basswood, sugar maple, bigtooth aspen, quaking aspen, and paper birch.
[3]Black ash, red maple, elm, yellow birch, white ash, white oak, northern red oak, and northern pin oak.

Climatic interactions between temperature and precipitation variables detrimental to growth are:

* high July temperature with low July precipitation (*i.e.*, drought stress in July)
* high precipitation and warmer temperatures in December.

Climatic interactions beneficial to growth are:

* high precipitation and low temperatures in March
* high precipitation and low temperatures in the fall.

Cold Weather Hardwoods

The strongest influences of single climatic variables beneficial to tree diameter growth are:

* high June precipitation
* low proportion of rainfall in the fall
* cold winters
* high number of days with intense precipitation ($\geq$ 0.5 inch) and moderate precipitation ($\geq$ 0.1 inch) in the summer.

Climatic interactions detrimental to growth are:

* drought stress in June
* warmer, wetter late fall (November) and winter.

Warm Weather Hardwoods

The strongest single climatic influences beneficial to growth are:

* warm winters
* high precipitation in the spring (along with high levels of intense and moderate precipitation in the spring)
* warm springs and summers
* warm falls.

Climatic interactions beneficial to growth are:

* wet, warm springs
* wet, warm winters.

These trends, although categorized by species group, usually tend to predominate in only some of the species in the group. For Group I those species are jack pine, red pine, white spruce, and balsam fir; for Group II they are sugar maple, bigtooth aspen, quaking aspen, and paper birch; and for Group III they are usually black ash, white ash, and occasionally northern pin oak. In Group III the remaining species may even show weaker effects in the opposite direction.

Certain differences appear between the conifer group and two hardwood groups:

* precipitation patterns shift for intense rainfall (fall precipitation is strongly beneficial to three conifer species; summer precipitation is more important to Group II hardwoods; and spring precipitation is more important to Group III hardwoods)
* increased July precipitation was related to increased conifer growth; increased June precipitation increased the growth of Group II hardwoods
* cold winters are beneficial to conifers and Group II hardwoods (of which many are found growing with conifers)
* warmer spring and summer temperatures affected conifer growth negatively, and Group III hardwood growth positively
* the magnitude of the average correlations indicates that conifers are more sensitive to climatic influences in the Lake States than are the hardwoods.

Some general observations can be made from the data analysis. Although all three temperature measures (minimum, mean, and maximum) showed similar correlations with tree diameter growth, the maximum or minimum value usually provided slightly more information than the mean value. Growing season temperature has less influence on tree growth than the cold season temperature, which alters the length of the growing season. Heavy precipitation ($\geq$ 0.5 inch) has a stronger relationship to tree diameter growth than moderate precipitation ($\geq$ 0.1 inch). In the colder part of the year, the proportion of precipitation is usually more important than the quantity. In the warmer months, the total amount is more important. Conifers grew faster when early snowfall came in November or late snowfall came in April; Group II hardwoods grew slower when there was very early snowfall in September. In general, however, snowfall had little effect on all tree species in the Lake States. Finally, annual precipitation and temperature values provide far less information than monthly or seasonal values.

The conifer results emphasize that a higher proportion of total precipitation and higher temperatures in December are detrimental to tree diameter growth. Rauscher (1984) identifies areas of the Upper Peninsula of Michigan next to Lake Superior as experiencing large amounts of precipitation in early winter and having mild winters.

Coefficients of determination (R^2) from the multiple regression analysis for the main climatic and climatic interaction variables were calculated for each tree species. The R^2 values (in percent) indicate the relative sensitivity to climate of the various Lake States tree species as follows:

Strong	Moderate	Weak
Jack pine (65)	Red pine (42)	Black spruce (14)
White spruce (66)	E. white pine (25)	Tamarack (11)
	Balsam fir (33)	N. white-cedar (13)
	Hemlock (45)	Red maple (9)
	Black ash (28)	Elm (7)
	Sugar maple (35)	Yellow birch (18)
	White ash (25)	Basswood (11)
	N. pin oak (25)	White oak (3)
	Bigtooth aspen (26)	N. red oak (2)
	Quaking aspen (34)	
	Paper birch (34)	

This part of the study has shown that after the STEMS model was used to adjust for differences in species, size, site, and competition, significant portions of otherwise unexplained variation in the tree diameter growth patterns for some species are accounted for by climatic variables.

SO_4 Deposition

Using average correlation coefficients, we determined the final predictor variables for SO_4 deposition and its interaction with stressful climatic variables (table 3). In almost all cases for Groups I and II the magnitude of the averages for SO_4 deposition x climatic interaction variables increases over SO_4 deposition alone and the number of species showing the effect nearly doubles.

Results of the multiple linear stepwise regression for each tree species (table 4) show the SO_4 deposition variables that entered the equation after the climatic and climatic interaction variables had entered. DEP1 to DEP11 refer to SO_4 deposition interactions with the stressful climatic-interaction variables; DEP refers to SO_4 deposition alone. Deposition and/or deposition x climate interaction terms entered into the regression model for 5 of 9 conifers and 6 of 13 hardwood species. Deposition x climate interactions entered 14 times; deposition alone entered only three times. Although statistically significant, the relationships are weak enough to contribute very little to increases in R^2 (except for jack pine, which shows a surprising 6-percent increase beyond an already high climatic component). The negative deposition effect is:

* stronger under stressful climatic conditions than alone
* strongest for jack pine, second strongest for red pine, and third strongest for white pine and bigtooth aspen (as measured by SO_4 deposition variables entering the regression equations and by strength of correlation coefficients of deposition variables with the growth errors).

A final observation is important. The correlation between January temperature and the SO_4 deposition is high ($r = 0.84$). Note the magnitude and direction of the correlations between tree diameter growth projection errors and January temperature and also SO_4 deposition (table 5). For all species with correlations $\geq |0.20|$ for January temperatures, 10 of 12 species had correlations of the same sign as SO_4 deposition. None changed signs. According to the sign test, this is a highly significant relationship ($P = 0.001$), and it indicates that the tree diameter growth responses to SO_4 deposition are essentially the same as those to cold temperatures. Where cold winters benefit growth, as with the conifers, it appears that low SO_4 deposition also benefits growth. The species that benefit from warm winter temperature (black ash and white ash of Group III) appear to benefit from SO_4 deposition. We see these trends in all three groups. So what is viewed as a SO_4 deposition effect may be primarily a temperature effect.

Table 4.—SO_4 *deposition variables entered into multiple linear regression equation after climatic variables were entered*

Species	R^2 (climatic only)	Deposition variables entered in:	Correl. coeff. of deposition variables with growth errors	Increase in R^2
GROUP I (Conifers)				
Jack pine	0.65	DEP3,DEP4,DEP2	-0.50,-0.45,-0.61	0.06
Red pine	0.42	DEP2,DEP4	-0.44,-0.35	0.01
White pine	0.25	DEP4	-0.27	0.01
White spruce	0.66	—		
Balsam fir	0.33	—		
Black spruce	0.14	—		
Tamarack	0.11	—		
N. white-cedar	0.13	DEP,DEP5	-0.10,-0.10	0.03
Hemlock	0.45	DEP2	-0.10	0.02
GROUP II (Cold weather hardwoods)				
Basswood	0.11	DEP	-0.10	0.02
Sugar maple	0.35	—		
Bigtooth aspen	0.26	DEP9	-0.30	0.01
Quaking aspen	0.34	—		
Paper birch	0.34	—		
GROUP III (Warm weather hardwoods)				
Black ash	0.29	—		
Red maple	0.11	DEP11,DEP,DEP10[1]	-0.13,-0.01,0.11	0.01
Elm	0.07	—		
Yellow birch	0.18	DEP10[1]	0.07	0.01
White ash	0.25	—		
White oak	0.07	DEP11[1]	0.06	0.02
N. red oak	0.02	—		
N. pin oak	0.22	DEP10[1]	0.21	0.01

[1]Deposition has a positive effect.

Table 5.—*Magnitude and direction of correlations between tree diameter growth projection errors and two highly correlated variables—January temperature and SO4 deposition levels*

Tree species	Correlations[1] of tree diameter growth errors with: January temperature	SO4 deposition
Jack pine	-0.51	-0.22
Red pine	-0.35	-0.21
White spruce	-0.50	-0.51
Balsam fir	-0.26	-0.18
Tamarack	+0.24	0.00
Hemlock	-0.30	0.00
Black ash	+0.30	+0.27
Yellow birch	-0.22	-0.21
Sugar maple	-0.31	-0.33
White ash	+0.42	+0.49
Bigtooth aspen	-0.42	-0.27
Quaking aspen	-0.28	-0.09

[1]Only January temperature correlations $\geq |0.20|$ were used to isolate the stronger relationships.

CONCLUSIONS

The results of this study show that after we adjust the tree diameter growth data for differences in species, size, site, and competition, much of the unexplained variation in the growth patterns can be accounted for by macroclimatic variables. The nature and magnitude of the relationships differ by tree species.

Tree species in the Lake States, especially conifers, showed the greatest response to fall and winter climate. Certain aspects of summer and spring precipitation were important, especially for the hardwoods. Spring temperature and precipitation are generally not as important to tree diameter growth in this region as they are in regions of more limited precipitation (Tryon *et al.* 1957).

The effects of SO4 deposition stresses on forests are difficult to separate from the effects of climate. Climate can cause changes in a forest that mimic or mask the effects of atmospheric pollutants. The data examined thus far make it impossible to conclude that SO4 deposition is a major factor affecting tree growth in the Lake States. However, SO4 deposition appears to have more influence on trees that are climatically stressed than on similar trees under no additional stress. The conifers, especially those growing on dry sites, seem to be more sensitive to SO4 deposition than the hardwoods, and jack pine is the most sensitive.

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Appendix A.—*Listing, by tree species groups, of the major variables, their mean and range in the study of climatic and SO4 deposition effects on tree diameter growth in the Lake States*[1]

Variable	Variable code	Statistics		
		Mean	Minimum	Maximum
GROUP I (Conifers)				
Avg. max. temp. cold season (Sept.-Feb.)	MAX T COLD	39.6	35.3	47.4
Avg. min. temp. warm season (Sept.-Feb.)	MIN T WARM	40.5	35.0	48.8
Prop. prec. Dec.	PROP P DEC	0.05	0.02	0.10
Prop. prec. March	PROP P MAR	0.06	0.04	0.09
Total prec. July	P JULY	3.6	1.9	5.1
Prop. prec. fall	PROP P FALL	0.26	0.20	0.33
No. of days prec. ≥ 0.1 inch summer	DP01 SUM	21.3	15.0	25.0
No. of days prec. ≥ 0.5 inch fall	DP05 FALL	5.2	2.0	7.0
No. of days temp. ≤ 0°F fall	DT00 FALL	0.9	0.0	4.0
Range (max. temp. July - min. temp. Jan.)	RANGE	73.1	59.1	85.1
Snowfall April (inches)	SNOW APRIL	3.7	0.9	10.8
High temp. with high prec. Dec.	TxP DEC	30.0	7.5	91.8
High prec. with low temp. Mar.	P/T MAR	0.07	0.04	0.11
High temp. with low prec. July	T/P JULY	19.3	13.3	35.9
High prec. with low temp. fall	P/T FALL	0.18	0.14	0.24
High SO4 dep. with low prec. July	D/P JULY	93.5	55.5	178.0
High SO_4 dep. with high temp. & high prec. Dec.	DxTxP DEC	250.3	142.2	449.3
High SO_4 dep. with high temp. & low prec. Mar.	DxT/P MAR	5.0	2.6	12.4
High SO_4 dep. with high temp. & low prec. July	DxT/P JULY	337.3	178.5	856.1
High SO_4 dep. with high temp. & low prec. fall	DxT/P FALL	555.1	87.7	2,771.9
High SO_4 deposition	D	17.2	11.03	30.6
GROUP II (Cold weather hardwoods)				
Avg. min. temp. winter	MIN T WINTER	3.7	-7.7	19.1
Prop. prec. Dec.	PROP P DEC	0.05	0.02	0.10
Prop. prec. March	PROP P MAR	0.06	0.04	0.09
Total prec. June	P JUNE	3.9	2.2	5.2
Prop. prec. fall	PROP P FALL	0.26	0.20	0.33
No. of days prec. ≥ 0.1 inch summer	DP01 SUM	21.6	15.0	25.0
No. of days prec. ≥ 0.5 inch summer	DP05 SUM	7.6	5.0	10.0
No. of days temp. ≤ 0°F winter	DT00 WINTER	37.1	4.0	60.0
Range (max. temp. July - min. temp. Jan.)	RANGE	73.5	58.5	85.1
Snowfall Sept.	SNOW SEPT	0.01	0.0	0.30
High temp. with low prec. June	T/P JUNE	16.1	12.2	27.2
High temp. with high prec. Nov.	TxP NOV	65.5	29.3	130.9
High temp. with high prec. winter	TxP WINTER	58.5	13.8	198.3

(Appendix 1 continued on next page)

(Appendix 1 continued)

Variable	Variable code	Statistics		
		Mean	Minimum	Maximum
High SO4 dep. with low prec. June	D/P JUNE	4.5	3.0	9.2
High SO_4 dep. with high temp. & low prec. June	DxT/P JUNE	280.3	190.8	566.3
High SO_4 dep. with high temp. & high prec. Nov.	DxTxP NOV	1,088.0	161.9	7,046.9
High SO_4 dep. with high temp. & high prec. winter	DxTxP WINTER	1,178.2	365.3	4,650.7
High SO_4 deposition	D	17.4	11.3	35.5
GROUP III (Warm weather hardwoods)				
Avg. max. temp. cold season (Sept.-Feb.)	MAX T COLD	40.4	35.3	47.4
Avg. mean temp. warm season (Mar.-Aug.)	MEAN T WARM	53.6	49.0	60.2
Total prec. Dec.	P DEC	1.63	0.79	3.84
Total prec. spring	P SPRING	7.9	5.2	11.0
Prop. prec. fall	PROP P FALL	0.26	0.20	0.33
No. of days prec. $\geq$ 0.1 inch spring	DP01 SPRING	18.2	14.0	26.0
No. of days prec. $\geq$ 0.5 inch spring	DP05 SPRING	4.9	2.0	7.0
No. of days temp. $\leq$ 0°F fall	DT00 FALL	0.8	0.0	4.0
No. of days temp. $\geq$ 90°F fall	DT90 FALL	0.2	0.0	2.0
High temp. with high prec. spring	TxP SPRING	330.6	208.1	506.0
High temp. with high prec. winter	TxP WINTER	64.0	13.8	227.2
High SO_4 dep. with low temp. & low prec. spring	D/(TxP) SPRING	0.32	0.14	0.85
High SO_4 dep. with low temp. & low prec. winter	D/(TxP) WINTER	0.06	0.04	0.09
High SO_4 deposition	D	18.2	11.3	35.5

[1]All temperatures are in degrees Farenheit, precipitation (including snowfall) are in inches, and SO_4 deposition is in kg/ha/yr.

Appendix B.—*Correlation (P ≥ 0.001) matrix (expressed as percents) for major variables used in the study by species*

GROUP I (Conifers)

Variable code	Tree species[1]								
	J.P.	R.P.	W.P.	W.S.	B.F.	B.S.	Tam	N.W.C.	Hem
MAX T COLD	-47	-32	—	-60	-41	—	20	-23	-15
MIN T WARM	-15	-32	—	—	-29	-17	20	-18	-32
PROP P DEC	-49	-28	-34	-38	—	—	21	- 9	—
PROP P MAR	34	38	—	27	18	25	—	—	-19
P JULY	53	39	16	43	27	—	-22	20	38
PROP P FALL	17	-19	-15	44	41	21	—	8	—
DP01 SUM	54	31	18	—	23	—	—	26	27
DP05 FALL	56	—	-18	49	42	—	—	18	21
DT00 FALL	55	33	—	61	31	—	-21	—	16
RANGE	46	36	17	30	—	—	-28	—	35
SNOW APRIL	11	—	-14	—	39	23	—	25	—
TxP DEC	-40	-30	-28	-43	-13	—	23	- 9	-19
P/T MAR	59	44	—	23	25	20	—	11	—
T/P JULY	-57	-39	-20	-39	-30	—	24	-23	-47
P/T FALL	57	13	-13	33	42	—	—	21	21
D/P JULY	-50	-35	-23	-49	-23	—	19	-18	-28
DxTxP DEC	-26	-25	-24	-41	-23	—	19	-18	-28
DxT/P MAR	-61	-44	—	-49	-39	-20	—	-20	—
DxT/P JULY	-49	-36	-22	-50	-26	—	20	-19	-30
DxT/P FALL	-51	-20	—	-67	-46	—	—	-21	-17
D	-22	-21	-17	-51	-18	—	—	-10	—
Number of observations	1,241	1,108	682	289	849	397	434	1,666	575

[1]J.P. = jack pine, R.P. = red pine, W.P. = eastern white pine, W.S. = white spruce, B.F. = balsam fir, B.S. = black spruce, Tam = tamarack, N.W.C. = northern white-cedar, Hem = hemlock.

GROUP II (Cold weather hardwoods)

Variable code	Tree species[2] B	S.M.	B.A.	Q.A.	P.B.
MIN T WINTER	-16	-28	-46	-33	-19
PROP P DEC	—	-29	-39	-26	-12
PROP P MAR	12	8	-20	-35	-21
P JUNE	18	29	29	46	56
PROP P FALL	-17	-43	-29	-37	-40
DP01 SUM	22	33	33	21	20
DP05 SUM	—	26	38	37	40
DT00 WINTER	19	35	45	31	17
RANGE	10	24	47	34	15
SNOW SEPT	-23	-38	-15	-10	- 9
T/P JUNE	-20	-27	-31	-47	-57
TxP NOV	-13	-25	-35	-30	-28
TxP WINTER	-13	-34	-39	-26	-15
D/P JUNE	-18	-36	-34	-34	-28
DxT/P JUNE	-18	-35	-34	-32	-27
DxTxP WINTER	-13	-31	-30	-22	-15
DxTxP WINTER	-13	-36	-34	-23	-15
D	-10	-33	-27	- 9	12
Number of observations	1,137	2,984	1,138	3,596	1,937

[2]B = basswood, S.M. = sugar maple, B.A. = bigtooth aspen, Q.A. = quaking aspen, P.B. = paper birch.

GROUP III (Warm weather hardwoods)

Variable code	Tree species[3]							
	B.A.	R.M.	Elm	Y.B.	W.A.	W.O.	R.O.	P.O.
MAX T COLD	42	—	16	—	43	—	—	—
MEAN T WARM	46	19	27	14	33	—	—	42
P DEC	20	-12	—	-15	44	—	—	-20
P SPRING	45	11	15	-13	36	—	—	33
P AUG	—	—	—	—	-32	-10	—	26
PROP FALL	-29	- 8	-15	-24	—	-14	—	-32
DP01 SPRING	27	—	—	—	35	—	10	—
DP05 SPRING	40	—	—	-21	23	10	—	32
DT00 FALL	-38	13	-16	28	-32	—	—	—
DT90	19	15	25	—	29	—	—	44
TxP SPRING	51	16	21	—	41	—	—	37
TxP WINTER	26	- 8	—	-20	47	—	—	-14
D/(TxP) SPRING	-24	11	-17	—	-35	—	—	21
D/(TxP) WINTER	-13	-13	-22	-18	19	—	—	-35
D	27	—	—	-21	49	—	—	—
Number of observations	709	2,297	513	650	302	1,245	1,944	1,427

[3]B.A. = black ash, R.M. = red maple, Elm = elm, Y.B. = yellow birch, W.A. = white ash, W.O. = white oak, R.O. = northern red oak, P.O. = northern pin oak.

Our job at the North Central Forest Experiment Station is discovering and creating new knowledge and technology in the field of natural resources and conveying this information to the people who can use it. As a new generation of forests emerges in our region, managers are confronted with two unique challenges: (1) Dealing with the great diversity in composition, quality, and ownership of the forests, and (2) Reconciling the conflicting demands of the people who use them. Helping the forest manager meet these challenges while protecting the environment is what research at North Central is all about.

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