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Regionally Averaged Diameter Growth in New England Forests

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Abstract

A regional sample of tree-ring measurements was used to determine average annual growth in trees of 10 major species in New England. There have been extended periods of decreasing growth rates in red spruce since about 1960 and in balsam fir since about 1965. The other eight species, which included sugar maple and white pine, showed constant or increasing growth rates through 1980. The decreases in growth rate in sampled red spruce and balsam fir were independent of physical site characteristics, elevation, and geographic location, indicating that regional factors are involved. Weather parameters and indexes were not closely correlated with growth rates, and the best predictive equation explained only 33 percent of annual variation. Due to past harvests and epidemics of the spruce budworm, much of the red spruce—balsam fir forest below 1,000 m in elevation can be considered to be functioning as even-aged. Historical growth information suggests that these trees should have reached maximum growth around 1960, and that decreasing growth rates since then are the result of normal aging.

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Cover Cross section from a representative New England red spruce. The center ring was formed in 1906. This tree probably germinated after overstory trees were felled for lumber or pulpwood. Such harvesting was widespread in the spruce-fir forests of New England around the turn of the century. Historical growth data suggest that the narrowing rings spanning the most recent 25 years are the result of normal aging.

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Introduction

Forest health has become a widespread concern in recent years in Europe, the United States, and Canada as scientists and others have noticed unusual foliage loss, narrowing ring widths, and increasing mortality. In the Eastern United States and Southeastern Canada, mortality and dieback of red spruce seem to have been increasing since the late 1960's and early 1970's. Concerns over red spruce have led to the closer inspection of other species such as sugar maple, balsam fir, eastern white pine, and white ash. Maple syrup producers are particularly concerned with recent foliar symptoms and diebacks of sugar maple (McLaughlin et al. 1985; McIlveen et al. 1986).

Some of the earliest reports of declining health were from studies of high-elevation red spruce forests in the Northeast (Johnson and Siccama 1983, 1984). These sites receive acidic precipitation and considerable fog and cloud moisture, which is even more acidic than rain and snow (Lovett et al. 1982). This has led to the suspicion that atmospheric deposition is an important influence on the health of high-elevation forests.

In the early 1980's, the Northeastern Forest Experiment Station was in the midst of a 10-year inventory of forest resources in New England.¹ More than 6,000 randomly located plots were surveyed for vegetation data and physical site characteristics. To determine stand age, one increment core was collected from each of four dominant or codominant trees adjacent to each plot. More than 20,000 cores were collected.

Ten commercially important tree species were well represented in this collection, providing a readily available source of information for assessing the growth and health of New England's forests. We used these increment cores to focus on four questions: 1. Did growth rates for any of the 10 species decrease recently for extended periods? 2. Is there a consistent pattern in the timing of any growth decreases? 3. Is there a consistent elevational or geographic pattern to any decreases? 4. Can growth patterns and trends be related to atmospheric deposition or other factors? We have attempted to answer these questions within the framework of the National Forest Response Program, which was established to address concerns about impacts of air pollution on tree health (Schroeder and Kiester 1989).

Methods

Field Sampling

The USDA Forest Service inventories each state at intervals of 10 to 15 years. Photo interpreters systematically locate thousands of points on aerial photographs. Ground plots are

determined from a stratified random subsample of these points. Single increment cores are obtained from each of four healthy dominant or codominant trees representing the major species on each ground plot. Cored trees are just outside the actual plot to prevent possible damage to trees on the permanent plot. Trees are cored parallel to the slope contour at breast height (1.37 m above ground). The recorded data for each tree include species, diameter at breast height (d.b.h.), tree height, sample date, and breast height age. Each core was stored in a straw that was labeled with the state and county codes, and plot and tree numbers. Stored cores were allowed to air dry within the partially sealed straws.

Core Preparation

Increment cores were mounted, with vessels or tracheids oriented vertically, in a shallow lengthwise cut in a block of kiln-dried softwood. Visibility of annual rings was enhanced by mechanically sanding or planing a radial surface of the core (Krusic et al. 1987). Annual rings in coniferous species have well-defined boundaries that are exposed by successive sandings of 220-, 400-, and 600-grit sandpaper followed by polishing with a wool buffing pad. Reflected light provided adequate illumination for measurement of all conifers.

Ring-porous hardwoods had to be planed because sanding occluded vessels and made the rings indistinct. Reflected light also is used when measuring these cores. Diffuse-porous hardwoods have poorly defined rings, especially in sapwood portions, and must be prepared carefully. We embedded the cores within a groove in a wood block and alternately planed both sides until the core was about 1.5 mm thick (Krusic et al. 1987). Transmitted light from a source beneath the core then makes the ring boundary appear more distinct.

Core Measurement

A digital micrometer accurate to 0.01 mm was used to measure annual rings. An attached microscope equipped with video camera and monitor magnified the core image so that annual rings could be discerned. Bundled fiber optics acted as the light source for both reflected and transmitted readings. The micrometer was interfaced with a microcomputer where software collected data and checked for operator input errors.

Cores were measured from the bark toward the pith. If a tree was cored before September 1 of the year of collection, the last annual ring was considered incomplete and was not used in subsequent data analyses. Some cores did not strike the pith. If only one or two annual rings were missed, the widths were estimated. The geometric center of the tree was located by making the arc of the boundary for the last visible ring congruent with a circle of known radius on a template (Liu 1986). The corresponding circle radius was entered into the data file along with the number of estimated years to the geometric center. This last measurement, which was useful for determining subsequent annual basal-area calculations, was excluded from our

¹ Forest Service resource inventory: an overview. 1985. USDA Forest Service, Forest Economics Research Staff, Washington, DC.

computations of mean annual basal-area increments by flagging the tree with an indicator variable.

Because of our study objectives and the need to measure a large number of increment cores in a short time, crossdating was done carefully, but not rigorously. There may be occasional errors due to missing rings, so our individual core data is not ideally suited for uses such as response analysis. Crossdating errors on our earliest analyzed red spruce increment cores were minimized by comparison with Marchand's high-elevation red spruce chronology (Marchand 1984). Marchand identified 1977, 1960, 1956, and 1948 as benchmark years for narrow annual rings. Our own red spruce chronology was developed after measuring approximately 1,000 cores. In addition to the years identified by Marchand, narrow rings were found in 1966, 1925, 1923, and 1921 while 1924 represented a large ring. The years 1966, 1956, and 1948 remained important for other species.

Our data files are available to the public. A description and examples of the files are given in the Appendix.

Data Analysis

Study regions were delineated by state boundaries except for Maine where the five northernmost counties, which had recent defoliation by spruce budworm, were separated from

the remaining 11 counties. Our first goal was to characterize growth trends for all the species in these regions. We chose to convert radial-increment measurements to basal-area increments (BAI), which represents the cross-sectional area of wood formed for a given period at breast height. Basal area is a commonly used measurement of both stand and individual tree development. Since ring widths tend to decrease in older and larger trees, BAI is a better indication of whether growth rates are decreasing (Phipps 1984). The annual BAI of the n th ring was calculated by:

$$BAI = (R_n^2 - R_{n-1}^2) \pi$$

where R is the tree radius obtained by summing ring widths. Mean annual BAI for each species was calculated by averaging over all trees with measured diameter growth for that year.

We usually present our results for the period 1900-80. Prior to 1900, with the exception of red spruce, there were too few trees from which to construct meaningful regional curves (Table 1). Red spruce is the only species with appreciable numbers before 1900 but many of these trees were suppressed. Their growth rates never were higher than the $1-2 \text{ cm}^2 \text{ yr}^{-1}$ around 1900, as shown in Figure 1. In addition, our geographic regions were sampled from 1980 through 1983 and took 1 to 2 years to sample. In many

Table 1.—Distribution of sample by species and age class

Species	Age class (years)											Total	Percent
	1-20	21-40	41-60	61-80	81-100	101-120	121-140	141-160	161-180	181-200	>200		
	<i>Number</i>												
Red spruce	11	149	883	744	543	274	160	105	40	25	67	3,001	31
Sugar maple	1	64	179	157	80	31	4	2	2	1	0	521	6
Red maple	22	226	211	167	44	14	2	0	0	0	0	687	7
White ash	3	79	149	55	36	8	2	0	0	0	0	332	4
Yellow birch	1	53	83	72	53	12	4	1	0	0	0	279	3
American beech	1	31	61	43	51	15	4	0	0	0	0	206	2
Red oak	7	199	302	192	40	10	0	0	0	0	0	750	8
Hemlock	1	64	160	166	142	45	27	7	2	0	0	614	6
Balsam fir	15	402	665	144	51	5	1	0	0	0	0	1,283	13
White pine	98	805	739	194	70	7	2	0	0	0	0	1,915	20

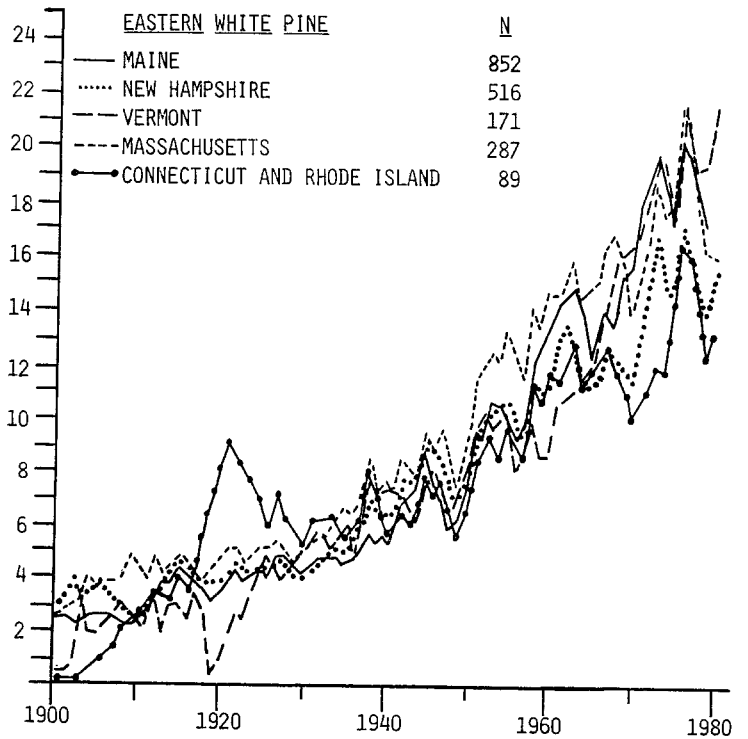
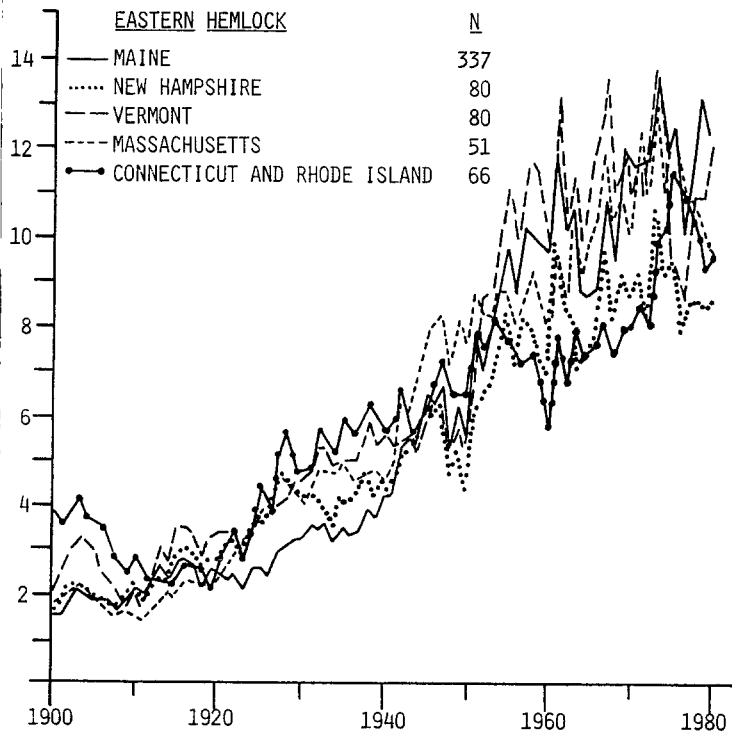
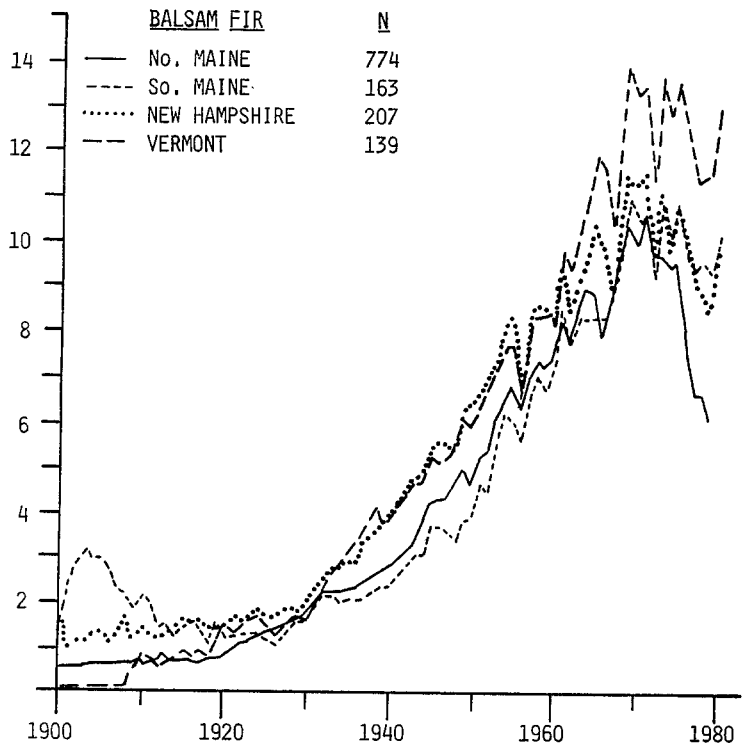
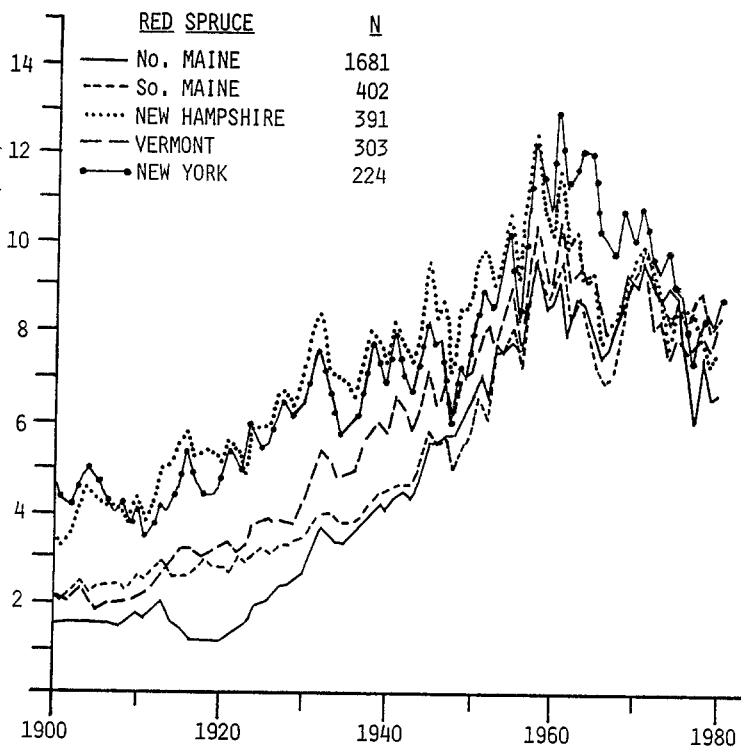


Figure 1.—Regional mean annual BAI (cm²) for red spruce, balsam fir, eastern hemlock, and eastern white pine.

instances, the last year of sampling in a region included too many trees with incomplete annual rings. The drop in the number of trees at the end of the regional curves gave a spurious fluctuation which was omitted by truncating the curves in 1980.

We also generalize about growth trends using polynomial regression equations for the period 1950-80, including only trees that were at least 50 years old at breast height in 1980 (Hornbeck et al. 1988). This period coincides with increasing exposure to atmospheric deposition and ensures a sample not biased toward very old or young trees. Annual BAI for each tree was normalized by dividing by the tree's average annual BAI over the period. The normalized BAI for each tree was then regressed against time to obtain linear (1st order) and curvature (2nd order) coefficients using the polynomial model:

$$b_{iy}/b_i = 1 + \alpha_i t_y + \beta_i (t_y^2 - 80) + \varepsilon_{iy}$$

where b_{iy} is the annual BAI for tree i and year y , b_i is the mean increment from 1950-80, and t_y is (year - 1965). The value of 80 is the mean of t_y^2 over the 31 years. The α_i and β_i coefficients were averaged over all trees within the species to generate a growth curve for that species. Mean annual BAI and the regression coefficients were tested between species by one-way ANOVA. Differences among species were tested with the Student-Neuman-Keuls test.

Results

Seventy percent of the 9,588 increment cores used for analysis were from softwoods (red spruce, eastern white pine, balsam fir, and hemlock) and 30 percent were from six hardwood species (Table 1). Thirty-one percent of the total cores were red spruce. The age structure of the sample reflects extensive harvesting in New England around the turn of the century. At the time of sampling, 80 percent of the trees were less than 80 years old at breast height and 60 percent were less than 60 years old. The age range of red spruce, with many trees over 200 years old, was the widest of any species. Sixty-five percent of the trees had inside bark diameters of 15 to 25 cm (Table 2). Ten percent of the sample, mostly red spruce and eastern white pine, had diameters in excess of 30 cm. Eastern white pine had more individuals over 30 cm in diameter than red spruce even though 95 percent of the white pine were less than 80 years old (compared to 60 percent for red spruce). The study sample generally is from low elevations; 70 percent of the trees were from elevations less than 400 m (Table 3). Six percent of the sample was from elevations above 700 m; most of these were red spruce.

Growth Patterns

Red spruce (Picea rubens Sarg.). Annual BAI of sampled red spruce increased from 1900 until about 1960 (Fig. 1).

Table 2.—Distribution of individuals by diameter class

Species	Diameter class (cm)										
	.1- 5.0	5.1- 10.0	10.1- 15.0	15.1- 20.0	20.1- 25.0	25.1- 30.0	30.1- 35.0	35.1- 40.0	40.1- 45.0	45.1- 50.0	50+
	Number										
Red spruce	1	7	195	985	972	493	192	89	34	20	13
Sugar maple	1	0	42	192	187	80	18	1	0	0	0
Red maple	0	2	115	281	198	75	16	0	0	0	0
White ash	0	1	33	112	121	47	16	2	0	0	0
Yellow birch	0	0	21	88	86	63	14	5	2	0	0
American beech	0	0	46	82	56	18	4	0	0	0	0
Red oak	0	2	89	296	249	87	21	4	0	0	2
Hemlock	0	0	31	143	230	125	65	14	5	1	0
Balsam fir	0	1	192	575	378	122	13	2	0	0	0
White pine	0	1	64	361	566	550	264	87	18	4	0

Table 3.—Distribution of individuals by elevation class

Species	Elevation class (m)											
	0– 100	101– 200	201– 300	301– 400	401– 500	501– 600	601– 700	701– 800	801– 900	901– 1000	1001– 1100	>1101+
	Number											
Red spruce	386	395	321	454	428	373	235	158	95	63	28	19
Sugar maple	26	19	21	78	114	112	83	51	16	0	0	0
Red maple	181	137	79	83	92	31	34	35	5	4	0	0
White ash	51	67	67	46	44	38	15	2	0	0	0	0
Yellow birch	16	22	10	22	40	60	43	39	15	7	3	0
American beech	13	31	44	45	36	10	18	4	2	0	2	0
Red oak	156	195	168	105	65	18	5	4	1	0	0	0
Hemlock	163	197	99	77	51	11	1	0	0	0	0	0
Balsam fir	196	168	219	229	216	109	44	23	27	21	8	22
White pine	656	651	267	186	91	45	4	0	0	0	0	0

The average for northern and southern Maine and Vermont rose to 9 to 10 cm² yr⁻¹ by 1960, while the average for New York and New Hampshire reached 12 cm² yr⁻¹ at the same time. After 1960, BAI decreased in the early 1960's, showed a slight recovery in all regions in the late 1960's, then continued to decrease until 1980. The overall decrease in BAI from the peak values around 1960 until 1980 ranged from 13 to 40 percent with the largest decreases found in New Hampshire and New York.

Balsam fir (Abies balsamea (L.) Mill.). BAI of sampled trees in all four regions steadily increased in all regions until between 1965-70 (Fig. 1). In 1970, the average BAI for all regions was 9 to 10 cm² yr⁻¹ except Vermont, where BAI was approximately 14 cm² yr⁻¹. After 1970, growth rates remained fairly stable or decreased. The particularly sharp decrease in northern Maine in 1975-77 was the result of an outbreak of spruce budworm (*Choristoneura fumiferana*).

Eastern hemlock (Tsuga canadensis (L.) Carr.). In all regions, BAI increased steadily to 11 to 13 cm² yr⁻¹ during the late 1970's (Fig. 1). New Hampshire and the combined region of Rhode Island and Connecticut had slower growth rates than the other regions after 1950, reaching 10 to 11 cm² yr⁻¹ by the mid-1970's.

Eastern white pine (Pinus strobus L.). Eastern white pine obtained by far the highest BAI's for any species that we

studied (Fig. 1). Growth rates steadily increased through the late 1970's and ranged from 17 to 22 cm² yr⁻¹.

Northern red oak (Quercus rubra L.). Growth rates in this species increased to 10 to 13 cm² yr⁻¹ by 1980 (Fig. 2). Rhode Island and Connecticut showed a growth decrease from the early 1950's to the early 1970's that has been attributed to drought and insect defoliation (Stephens and Hill 1971). In 1980, single-year growth decreases of as much as 37 percent occurred in Connecticut, Rhode Island, Massachusetts, and Vermont due to an epidemic of the gypsy moth (*Lymantria dispar*).

White ash (Fraxinus americana L.). Growth rates in sampled white ash increased slowly from 1900 to 1940, averaging 3 to 4 cm² yr⁻¹ (Fig. 2). Growth rates accelerated in all regions after 1940 and reached maximums of 11 to 13 cm² yr⁻¹ by the late 1970's. Trees in Vermont and Massachusetts outgrew those in other regions during this period. Growth reductions in several regions from 1978-80 are unexplained.

Red maple (Acer rubrum L.). Red maple growth rates steadily increased to 9 to 11 cm² yr⁻¹ by 1980 (Fig. 2). All regions apparently were affected by a drought in the early 1960's. Connecticut and Rhode Island did not show a substantial growth recovery until the mid 1970's compared to a recovery in the mid to late 1960's for the other regions. New Hampshire growth rates dipped the most due to the

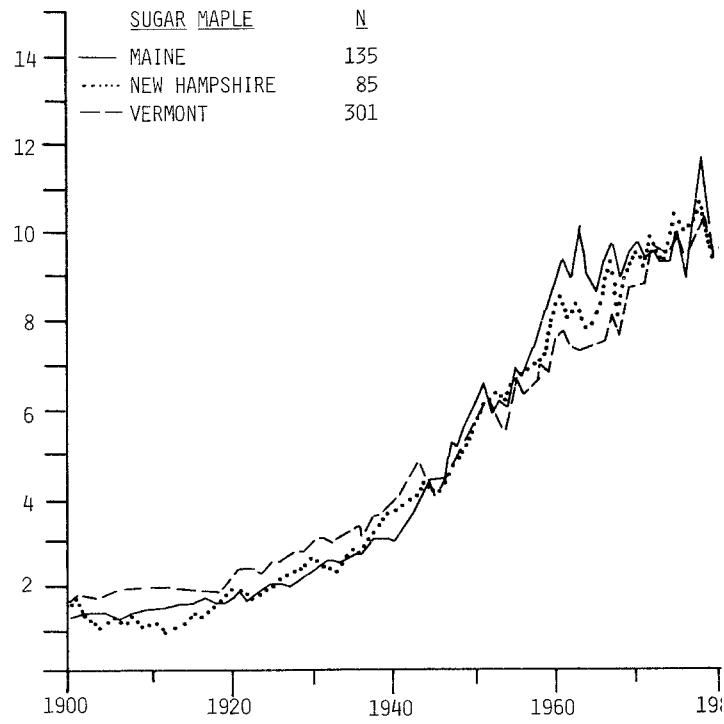
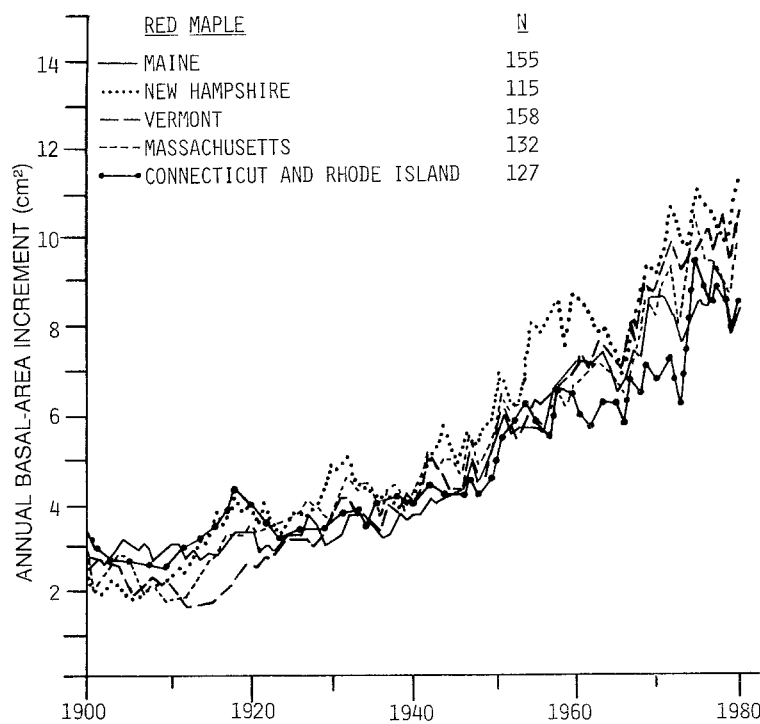
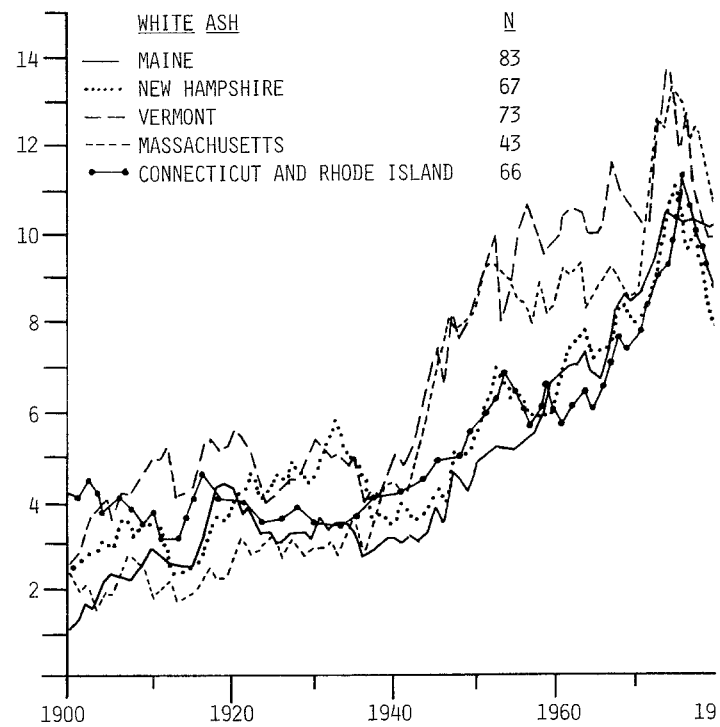
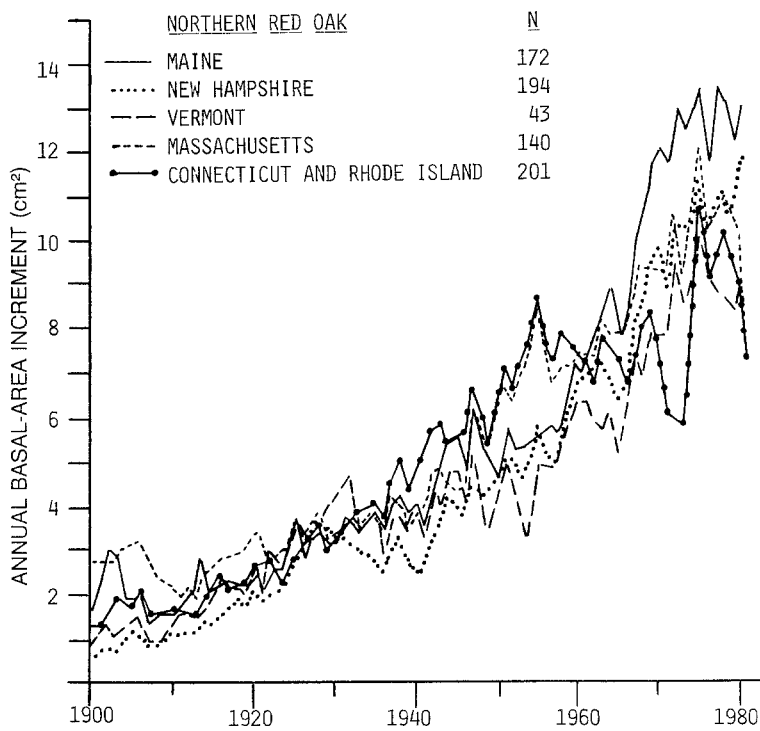


Figure 2.—Regional mean annual BAI (cm²) for northern red oak, white ash, red maple, and sugar maple.

1960's drought, but this region had a faster growth rate for the 10 years preceding the drought.

Sugar maple (*Acer saccharum* Marsh.). Growth rates steadily increased in all regions to 10 to 11 $\text{cm}^2 \text{yr}^{-1}$ by 1980 (Fig. 2). Decreases in growth during the early 1980's in Vermont and New Hampshire can be attributed to defoliation by gypsy moth, forest tent caterpillar (*Malacosoma disstria*), and the saddled prominent (*Heterocampa guttivitta*.)

Yellow birch (*Betula alleghaniensis* Britt.). Vermont, New Hampshire, and Maine were the only states containing sufficient quantities of yellow birch for analysis. Growth rates reached levels of 11 to 12 $\text{cm}^2 \text{yr}^{-1}$ by the early 1970's, and then leveled off through the early 1980's (Fig. 3).

American beech (*Fagus grandifolia* Ehrh.). Growth rates were uniform at 1 to 2 $\text{cm}^2 \text{yr}^{-1}$ from 1900 until the late 1930's (Fig. 3), then increased steadily from 1940 and attained rates of 9 to 10 $\text{cm}^2 \text{yr}^{-1}$ by 1980. All regions showed a slight growth depression from 1960 through 1965.

All species. Figures 1-3 suggest that often there are simultaneous increases or decreases in annual growth over several or all regions. Common influences such as weather, forest aging, insect attacks, or other forest perturbations may be responsible for these synchronized growth events. An exception to this regional synchronicity occurred in the Rhode Island-Connecticut species. From 1950 to 1970, species in this region showed fairly constant growth as opposed to generally increasing trends in other regions.

Graphs of BAI for all 10 species indicate that red spruce has been undergoing a growth decrease since 1960; that balsam fir shows a similar decrease after the middle to late 1960's, and that the other species show no obvious long-term decreases in annual BAI (Figs. 1-3). A further analysis of differences between species for the period 1950-80 substantiates these findings (Fig. 4, Table 4). These years span the period of concern over impacts of atmospheric deposition. We chose trees that were at least 50 years old at breast height in 1980 so that some growth would have occurred prior to the era of increasing atmospheric deposition levels after 1950.

Eight of the 10 species had positive linear coefficients that measured the rate of change in growth (Table 4). Growth was increasing most rapidly in American beech. White pine, yellow birch, sugar maple, red oak, eastern hemlock, and white ash had positive linear coefficients that were significantly greater than zero but were not significantly different from each other. Balsam fir and red spruce had negative linear coefficients, indicating a downward growth trend, though balsam fir's was not significantly different from zero.

The curvature coefficient represents the change in the rate of change of growth. American beech, white ash, red maple, white pine, red oak, and sugar maple had positive coefficients, though only beech and white ash had coefficients significantly greater than zero, indicating that growth rates of these two species were increasing the fastest. Hemlock, yellow birch, red spruce, and balsam fir had negative coefficients. Balsam fir and red spruce were

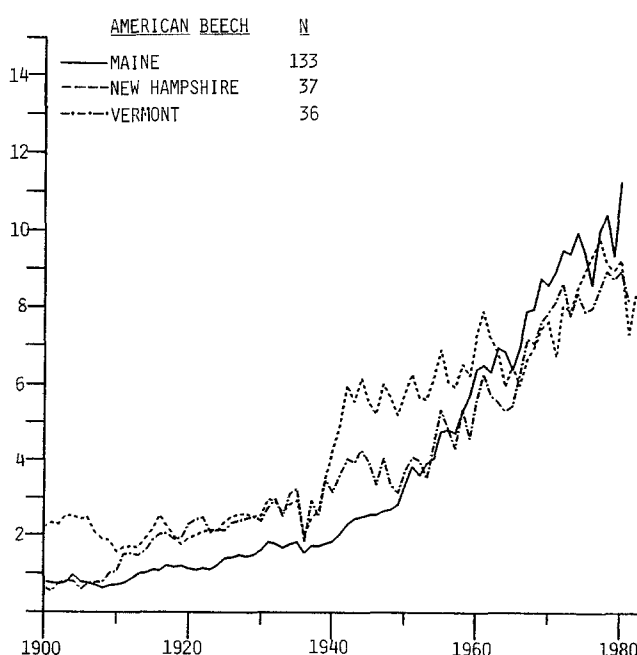
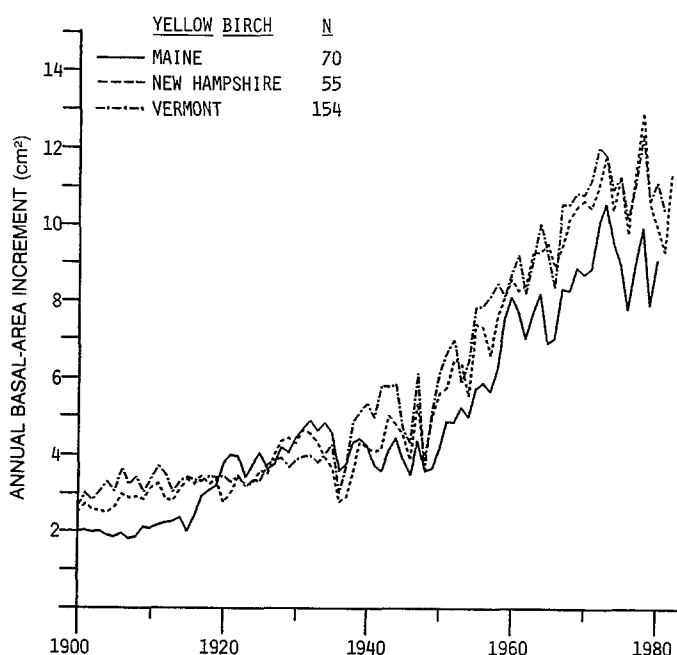


Figure 3.—Regional mean annual BAI (cm^2) for yellow birch and American beech.

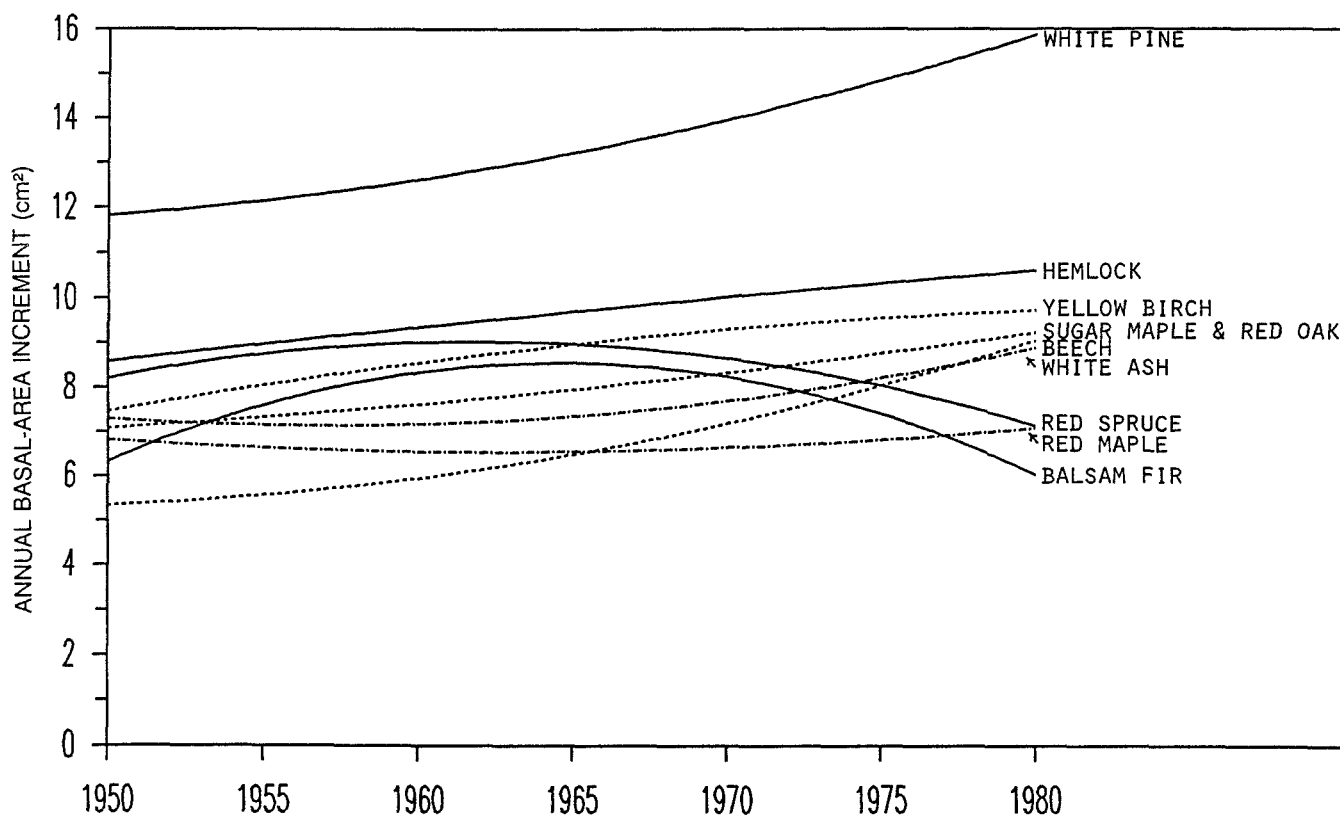


Figure 4.—Regional growth curves for major species in New England forests, 1950–80.

the only species with curvature coefficients significantly less than zero. Balsam fir growth was decreasing more rapidly.

The species curves (Fig. 4) confirm that red spruce and balsam fir are the only sampled species in New England showing extended periods of decreasing growth in recent years. Growth of red spruce has been decreasing since about 1960 while growth of balsam fir generally began decreasing slightly later. American beech and white ash have the fastest accelerating growth rates toward the end of the 1950–80 period. The remaining species tend to have a constant positive rate of change over the study period.

Detailed Analysis of Red Spruce

The growth decreases evident in the regional BAI curves of red spruce warranted a more detailed analysis of this species since our findings agree with earlier studies pointing to slowing growth starting around 1960. The timing and spatial dimension of the growth decrease relates circumstantially with atmospheric deposition which has increased regionally since the late 1940's. However, detailed records of regional atmospheric deposition over this timespan are not available, so direct analysis of impacts on annual growth rates are not possible. Other possible causes of the decrease must be ruled out before

atmospheric deposition can be assumed as the cause. Thus we concentrated on investigating other possible explanations for the growth trends.

Age and Size Classes

The regional curves were recalculated by age and size classes to determine if certain ages or sizes of trees were causing the mean annual BAI to decrease after 1960. The sample from northern Maine, which is representative of the trends in the other recalculated regional curves, was divided into four age classes as of 1980: 50 years or less, 51 to 70 years, 71 to 90 years, and 91+ years. All four age classes had similar patterns after 1960, showing growth decreases until the mid-1960's, recoveries to pre-1960's levels by 1970, and then further growth decreases after 1970 (Fig. 5). This later growth decrease coincides at least partly with a spruce budworm epidemic that began in 1975.

These same trees also were assigned to three size classes based on diameter in 1980: less than 20 cm d.b.h., 20 to 30 cm d.b.h., and 31+ cm d.b.h. Although larger diameter classes grew at higher absolute rates than smaller diameter classes, the timing and direction of growth fluctuations after 1958 coincided for all three diameter classes (Fig. 6). The data suggest that growth decreases after 1960 are independent of tree size and age.

Table 4.—Mean annual BAI, mean regression coefficients and standard deviations for the period 1950–80; vertical lines connect species that are not significantly different by the Student-Neuman-Keuls test; range test on mean annual increment carried out on log-transformed values to homogenize the variance; $\bar{w}$ is defined in [1]

Species	Mean	s	n	$\bar{w}$
Mean Annual BAI				
White pine	13.4	6.9	511	.101
Hemlock	9.7	5.6	450	.146
Yellow birch	8.8	5.2	183	.159
Red spruce	8.5	4.9	2302	.160
Red oak	8.1	4.0	379	.158
Sugar maple	8.0	4.1	338	.162
Balsam fir	7.7	3.6	359	.163
White ash	7.6	4.5	143	.179
American beech	6.7	3.4	137	.203
Red maple	6.7	3.4	296	.192
Linear Coefficient $\times 10^3$				
American beech	25.2	32.9		
White pine	13.6	33.1		
Yellow birch	12.1	28.5		
Sugar maple	11.7	29.6		
Red oak	10.8	21.5		
Hemlock	9.9	28.6		
White ash	9.6	25.5		
Red maple	1.8	27.9		
Balsam fir	-1.5	30.5		
Red spruce	-5.7	27.8		
Curvature Coefficient $\times 10^3$				
American beech	0.64	2.87		
White ash	0.59	1.75		
Red maple	0.33	2.16		
White pine	0.28	2.59		
Red oak	0.19	1.46		
Sugar maple	0.14	2.47		
Hemlock	-0.07	2.24		
Yellow birch	-0.27	2.39		
Red spruce	-0.93	1.93		
Balsam fir	-1.72	1.94		

[1] Mean growth curve for each species:

$$b_y = \bar{b} + t_y \bar{\alpha} / \bar{w} + (t_y^2 - 80) \bar{\beta} / \bar{w}$$

$$w = (1/n) \sum (1/b_i)$$

Elevation

Earlier reports of decline symptoms and mortality of red spruce in the Northeast were limited to sites with elevations ranging from 800 to 1,100 m (Johnson and Siccama 1984; McLaughlin et al. 1987). These elevations are higher than those associated with the commercial spruce-fir forests of the region and are subjected to different environmental impacts. Ninety-three percent of our red spruce sample spanned elevations from near sea level to 800 m, and nearly

100 percent were from elevations less than 1,000 m (Table 3). This provided a means to determine if declining growth in commercial forests is associated with increasing elevation. A linear regression equation was fit to each tree's annual BAI measurements from 1960 through the last complete annual ring. The majority of trees had negative regression coefficients and scatter plots, indicating that declining growth is independent of elevation. Figure 7 illustrates this point for New Hampshire, which had the widest elevation range of any of our study regions.

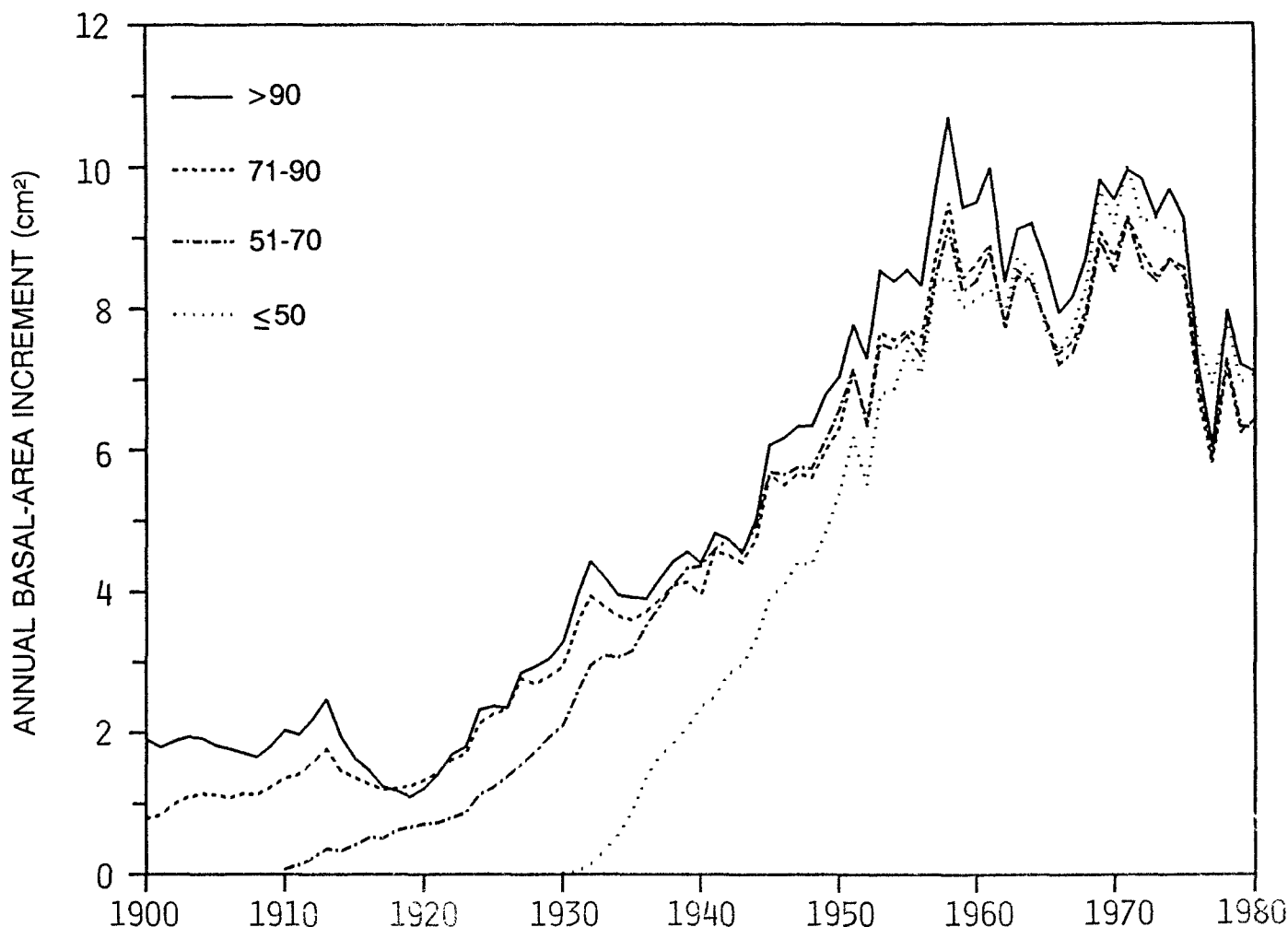


Figure 5.—Red spruce mean annual BAI for four age classes in northern Maine.

Factors Affecting Growth

Several factors or combinations of factors may be involved in the decreasing growth rates of red spruce that have occurred since 1960. These include acid deposition, insects and diseases, regional weather events, and the normal process of tree maturation. The data base on acid deposition is temporally and spatially weak, making it difficult to develop regional relationships between growth patterns and deposition. Insects and diseases, at least those known to be important in the past, do not seem major factors in the decline. The spruce budworm has been active at times since 1960, the last example being a sharp decrease in growth from 1975-77 in the northern Maine sample (Fig. 5). However, overall activity of the budworm does not coincide with the start of the decrease in growth rates around 1960 (Hardy et al. 1986). In addition, the regional curves for southern Maine, Vermont, and New York, areas free of recent budworm activity, are similar during the decline period to those for northern Maine and New Hampshire, which have a history of budworm activity (Fig. 1). *Armillaria* root disease also has been ruled out as a major factor (Carey et al. 1984). We have studied the role of

the remaining two factors, regional weather and tree maturation. We also have attempted to determine if growth rates are related to some of the site variables measured on each inventory plot.

Maturation. The red spruce forests in this region were heavily logged around the turn of the century and also subjected to severe attacks by spruce budworm from 1912-20 (Seymour 1985). In northern Maine, southern Maine, and Vermont, 57 to 68 percent of our sample trees are in the 41- to 80-year age classes and 79 percent are between 41 and 100 (Table 5). New York trees have a much broader age distribution, with New Hampshire intermediate. In terms of size, 66 to 73 percent of the trees in Maine and Vermont were 15 to 25 cm in diameter, with lower percentages in New Hampshire and New York (Table 6). The changing diameter distribution of the northern Maine trees over time verifies the even-aged, even-sized nature of the Maine forest as described by Seymour (1985) (Fig. 8). Red spruce's ability to survive long periods of suppression and to respond when released suggests that some of the remaining 20 percent of our age sample, trees that are older than 100 years, are growing like younger trees after being

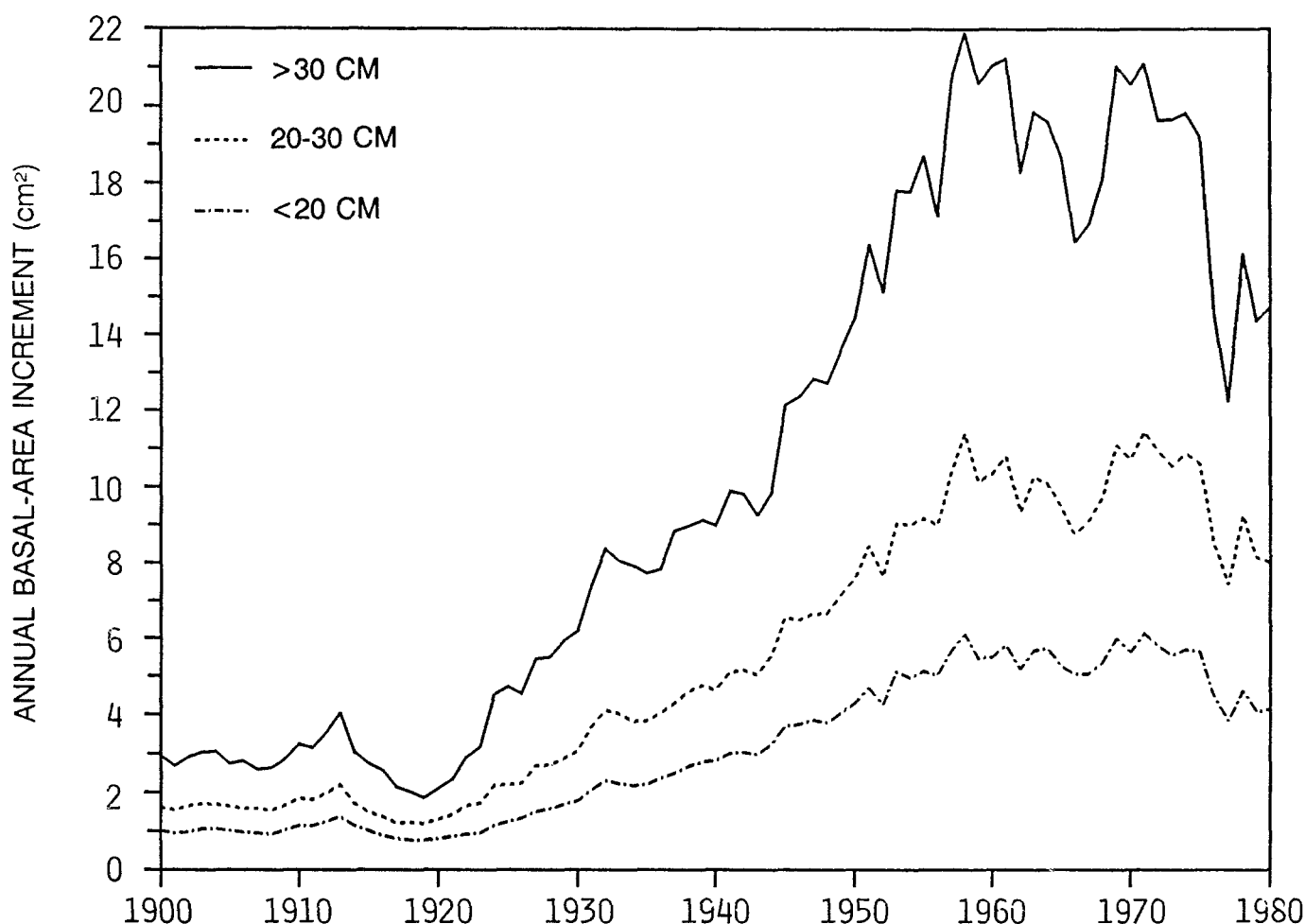


Figure 6.—Red spruce mean annual BAI for three diameter classes in northern Maine.

released by logging or widespread mortality of overstory trees due to the 1912-20 budworm epidemic. Physiological age may differ considerably from chronological age in red spruce.

Data collected by Meyer (1929) were used to determine if our regional curves from 1900 through 1980 were as expected for an even-aged red-spruce forest (Hornbeck et al. 1986). Meyer collected data in the 1920's from 201 second-growth even-aged stands that had colonized abandoned fields in Maine, New Hampshire, and Vermont. His data for mean stand diameter in 10-year intervals were converted into annual BAI after fitting the data by Weibull functions (Federer and Hornbeck 1987). Meyer stated that red spruce seedlings reach breast height in about 15 years and adjusted his age data for this. The past insect attack and cutting histories indicate that many of our sample trees probably originated from suppressed advance reproduction and seed during this period, and may have reached breast height between 1905 and 1925. Shifting the curve derived from Meyer's data to start at breast height in 1915 and superimposing it over our mean annual basal-area curves provides a close match (Fig. 9). Meyer's stand basal-area

and density estimates approach asymptotes after stand ages of 80 to 100 years, indicating that mean tree BAI curves must reach a maximum and then decline (Federer and Hornbeck 1987). This is exactly what our regional annual BAI curves show. Meyer's data also predict a constant radial increment initially, followed by a decrease, just as our trees do (Fig. 9).

Although Meyer's data were obtained for old-field successions, they have been and still are used successfully to predict tree growth in all spruce-fir forests in northern New England. The excellent agreement of our BAI and radial increments with Meyer's data and the 1915 initiation date cannot be coincidental. The northeastern red spruce forest as a whole is growing as if it were an even-aged stand that reached breast height around 1915.

On the other hand, the New York red spruce and, to some extent, New Hampshire red spruce are not even-sized or even-aged. This may explain why they have the highest average BAI values. The fact that they also reached a peak BAI around 1960 argues that factors other than maturation are involved in the regional synchrony of the growth

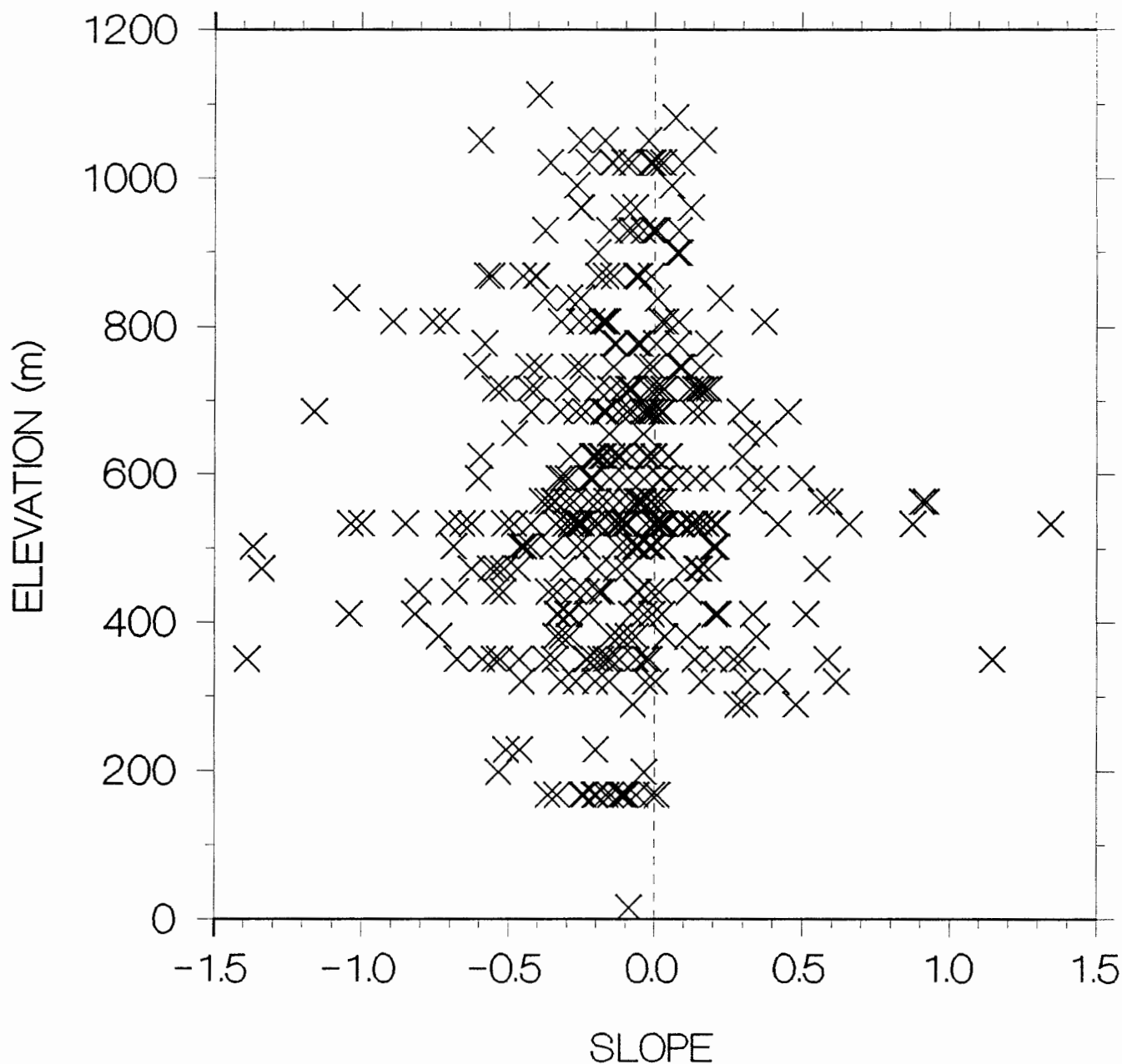


Figure 7.—Slope of BAI 1960–82 vs. elevation for New Hampshire red spruce.

decrease. Regional weather events might have induced this synchrony.

Regional weather. The similar timing of many increases or decreases in annual BAI among the regions indicated that weather might be an important factor in determining interannual variation of BAI. Standard dendroclimate work on red spruce has related monthly precipitation and temperature to detrended ring width series by use of multiple regression. Cook et al. (1987) and Conkey (1979) found that diameter growth in red spruce was positively

correlated with the current growing season's May and September temperatures as well as early winter temperatures of the previous year. They found negative correlations between diameter growth and the previous year's July, August, and October temperatures. The previous year's July or August precipitation was weakly correlated with diameter growth while the current year's precipitation had no effect. These studies accounted for less than 30 percent of the variance in diameter growth.

To increase the variance explained by multiple regressions

of weather data on diameter growth, Federer et al. (1989) used daily temperature and precipitation to construct more complicated variables based on physiological growth responses and on soil-water deficits derived from the BROOK model (Federer and Lash 1978). The National Climatic Data Center provided daily precipitation and daily maximum and minimum temperatures for 1926 through 1980 from 14 weather stations in northern New England and northeastern New York. The stations were grouped into three regions: Maine, New Hampshire and Vermont, and the Adirondack Mountains of New York. Within each region daily values were averaged. A detrended time series for each region was derived by fitting a cubic smoothing spline (Cook and Peters 1981) with a period of 50 to the mean

annual BAI measurements for each region (Fig. 10). These indexed series were standardized by taking the ratio of the actual mean annual BAI to the fitted cubic-spline value. Autocorrelation was removed from each regional series by fitting with an AR(1) model (Cryer 1986).

Three multiple regression models were tested using the detrended and delagged BAI time series: I: a standard dendroclimate model based on daily weather values; II: a model using variables based on seasonal temperature and soil-water deficit; III: a model with seasonal estimates of photosynthesis and respiration based on temperature and water deficit. If one of the variables used in any of the models was significant in one of the regions, it was entered

Table 5.—Distribution of red spruce ages by geographic area and percentage of sample

Location	Age (years)											Total
	1– 20	21– 40	41– 60	61– 80	81– 100	101– 120	121– 140	141– 160	161– 180	181– 200	>200	
	Percent											Number
No. Maine	0	3	34	23	21	10	5	3	1	0	0	1,681
So. Maine	1	10	32	33	14	5	3	1	1	0	0	402
New Hampshire	0	4	17	23	20	12	9	7	2	2	4	391
Vermont	1	14	35	33	11	3	2	1	0	0	0	303
New York	0	0	8	14	9	11	13	9	8	7	21	224

Table 6.—Distribution of red spruce diameters by geographic area and percentage of sample

Location	Diameter class (cm)										51+
	0.1– 5.0	5.1– 10.0	10.1– 15.0	15.1– 20.0	20.1– 25.0	25.1– 30.0	30.1– 35.0	35.1– 40.0	40.1– 45.0	45.1– 50.0	
	Percent										
No. Maine	0	0	7	38	35	15	4	1	0	0	0
So. Maine	0	0	9	38	31	14	5	2	1	0	0
New Hampshire	0	1	4	20	28	20	11	6	3	4	3
Vermont	0	0	7	32	34	19	5	3	0	0	0
New York	0	0	2	10	23	24	21	13	6	1	0

into the regressions for the other two regions so that the results were comparable.

In Model I, the previous July-August temperature, winter temperature, and the September temperature were significant in at least one of the regional series (Table 7), in agreement with other dendroclimate studies of red spruce (Conkey 1979; Cook et al. 1987; McLaughlin et al. 1987; Kimball and Kiefer 1988). Diameter growth is negatively correlated with the previous year's June-July temperature and positively correlated with winter temperature and September temperature.

Model II included six variables: early season degree days, late season degree days, previous late season degree days, early season soil-water deficit, late season soil-water deficit, and previous late season soil-water deficit. The previous late season degree days was the only variable of any predictive significance in this model and it was negatively correlated with growth (Table 7).

Model III was based on seasonal estimates of photosynthesis and respiration using the same season lengths as in Model II. Daily photosynthesis was reduced by the daily ratio of actual to potential evapotranspiration as simulated by the BROOK model. Seven variables were constructed from this data: early season photosynthesis, late season photosynthesis, previous late season photosynthesis, early season respiration, late season respiration, previous late season respiration, and winter respiration. The previous year's late growing season respiration and winter respiration were the only significant variables in this model (Table 7). Winter respiration was positively correlated with growth while the late season respiration was negatively correlated with growth.

The physiologically based models II and III were outperformed by the standard dendroclimate Model I (Federer et al. 1989). The dendroclimate model explained from 18 to 33 percent of the variation for the three regions (Table 7), which is typical of other dendroclimate models. The maximum variance explained for the other two models was 17 percent. Neither physiologically based model was able to explain any significant variance in Maine. The previous late season degree days of Model II and the previous late season respiration from Model III are alternative expressions of the previous late season temperature used in Model I. Detrending and delagging of the annual BAI time series removed any association of the current and previous year's growth controlled by the previous season's weather. The effects of the previous year's late season temperature on current growth are additional effects not related to the previous years growth (Federer et al. 1989), and may reflect reductions in the stored carbohydrate pool due to higher respiration. The positive correlation between winter temperature and the current year's growth in Model I also may reflect the amount of metabolic products produced for hardening physiology. The association of current year's growth and September temperature may be a spurious correlation in our data due to the warm September in 1961 (Federer et al. 1989).

Relationships to site variables. We investigated whether site characteristics were related to the declining growth of red spruce. Principal components analysis (PCA) and factor analysis (FA) were used to group correlated variables so that hypotheses could be generated about relationships between constructed growth variables and site variables.

After screening potential variables, four related to growth and seven related to site were chosen for analysis. The constructed growth variables included the linear and curvature growth coefficients of individual trees derived from 1950-80 as well as the mean BAI and the basal area at the midpoint of this same period for individual trees. The linear and curvature coefficients were used as indicators of tree decline. Some site variables had too few categories to be used in either PCA or FA and had to be converted into two-level variables. The converted variables were recent harvest/non-harvest, shallow rooted (0- to 10-inch depth)/non-shallow rooted, sandy soil/non-sandy soil, and dry/non-dry sites. Other site variables were elevation, organic depth, and total-plot basal area.

The four growth indices and seven site variables were analyzed by PCA to determine how many of the 11 possible factors would be retained in subsequent FA. Factors containing large amounts of variance from the correlation matrix usually are retained (Tabachnick and Fidell 1983) while those factors accounting for little variance are discarded from later FA. The PCA indicated that five factors should be used in the FA.

Of the five factors generated in the FA, two or three variables usually defined each factor (Table 8). The most important factors lead to conclusions that are expected. The first factor was dominated by the mean BAI value for the period and the basal area at the midpoint of the period; large trees tend to have a higher mean BAI compared to smaller trees. The second factor indicated that unharvested plots had higher basal areas. The third factor states that dry sites, which have shallow organic horizons, tend to have deeper rooted trees growing on them. The fourth factor loaded heavily on the linear regression term and marginally on the midpoint basal area and mean annual BAI for the period. This factor was associated with small basal-area trees that were in the ascending portion of their growth curve. The last and least important factor had marginal loadings on elevation, sandy soil, and the curvature coefficient. Although our work and that of others have shown that declining growth rates are independent of elevation, increasing elevation was weakly associated with the fastest decreasing growth rates and with less sandy soils.

The least important factor was the only one that included a relationship between a growth variable and a site variable. The lack of strong relationships between the two types of variables may mean that we constructed the wrong growth indicators, that the two-level variable categories were too broad, or that there is no link between constructed growth indicators and the available site variables.

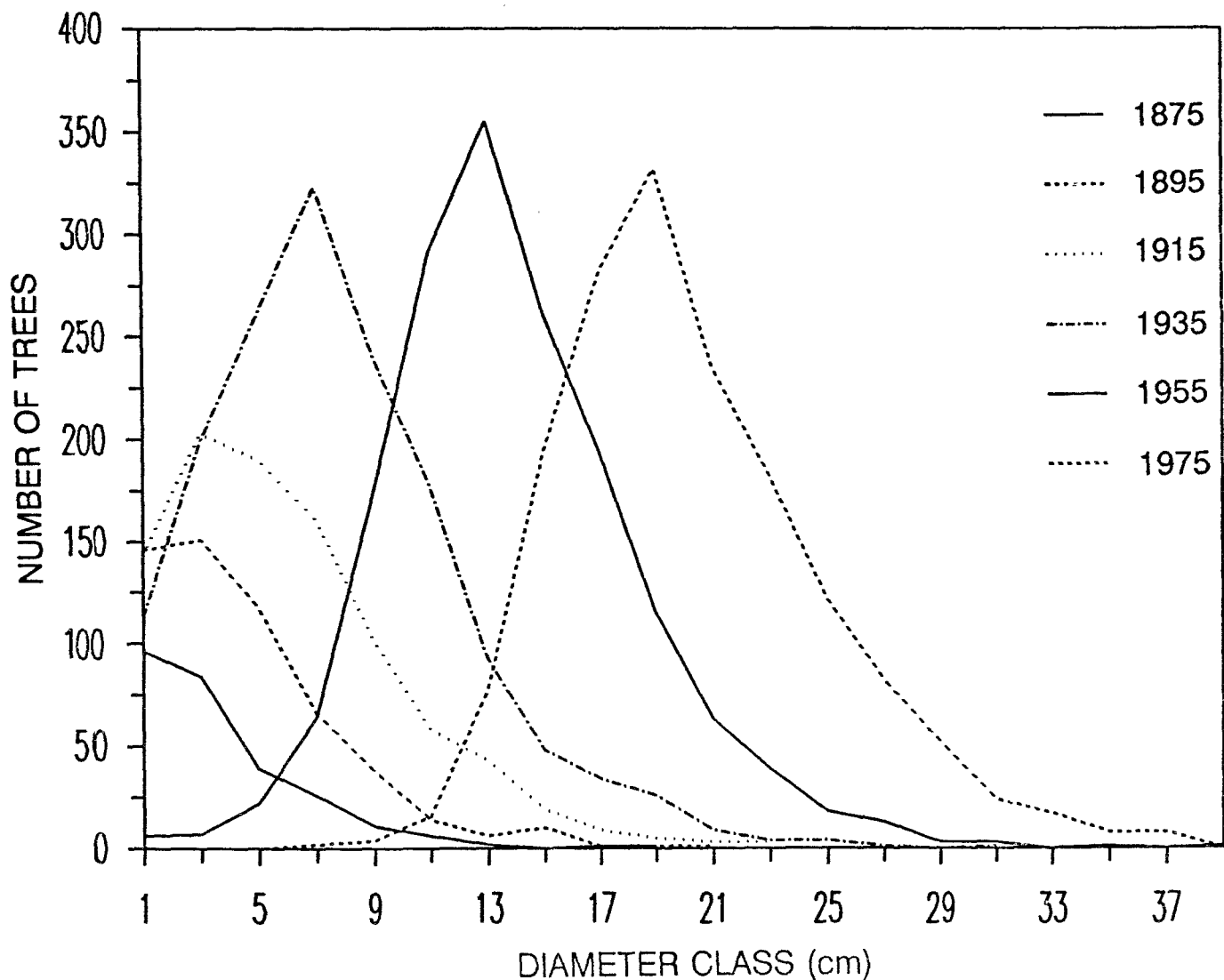


Figure 8.—Diameter distributions for northern Maine red spruce at 20-year intervals, 1875–1975.

Growth Patterns During Senescing Years

Although red spruce mortality has been studied from a stand perspective (Weiss et al. 1985), individual-tree growth patterns preceding death have not been examined. We conducted two separate studies of dead trees to determine if growth information could be recovered from trees in varying stages of decay, and to see if there were common growth patterns preceding death in trees that died years apart.

The first study took place in the fall of 1986. We took disks from 15 standing and fallen dead trees from an east-facing

site at an elevation of 800 m on Mt. Washington in New Hampshire. Disks that contained large amounts of decay were impregnated with a wood glue to preserve their physical structure before being banded and buffed.² Four radii from each disk were crossdated and subsequently measured on the digital micrometer. A mean radius for the tree was constructed by averaging the two longest radii.

² Krusic, P. J.; Hornbeck, J. W. 1989. Preserving decayed wood samples for tree-ring measurement. Submitted to Tree-Ring Bulletin.

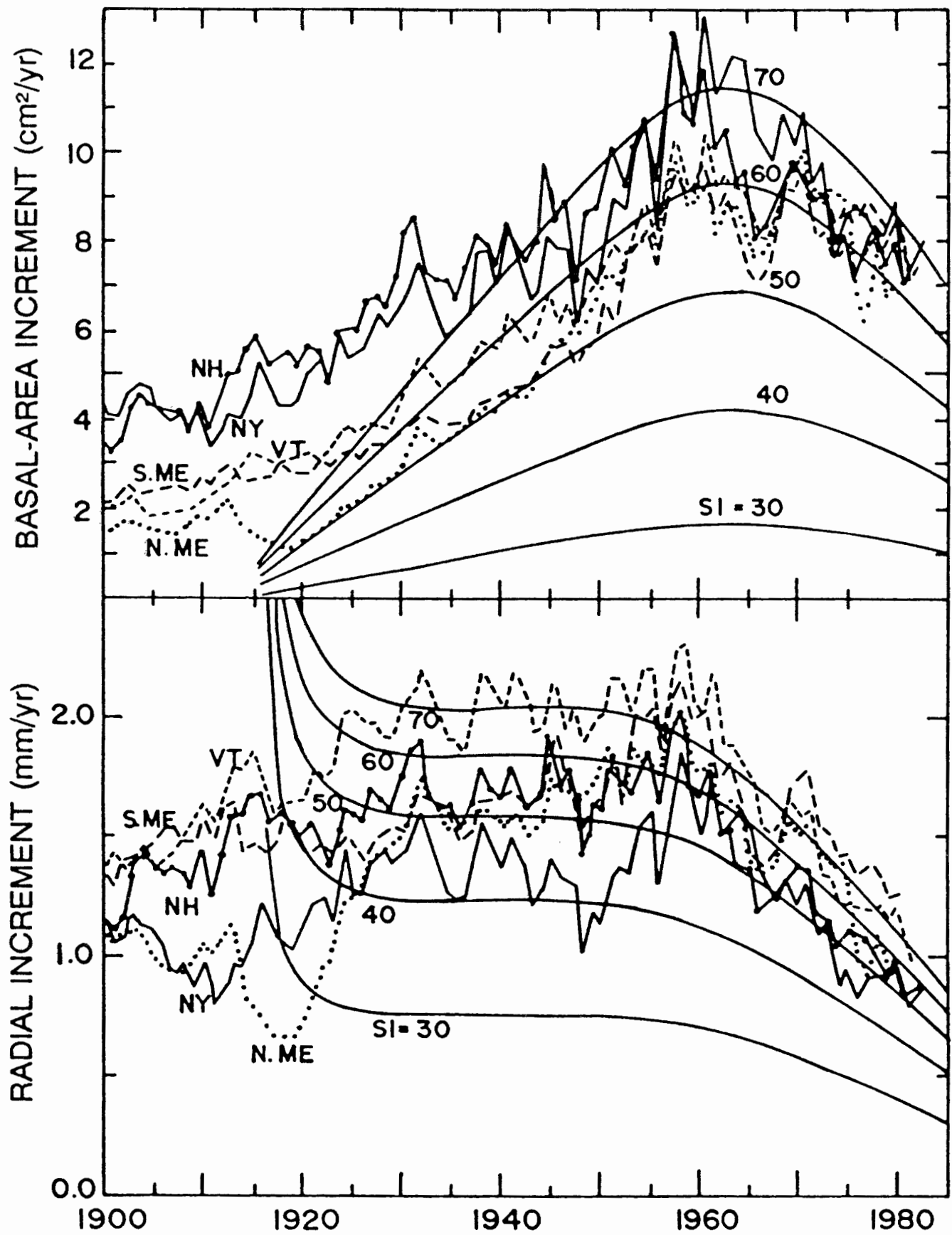


Figure 9.—Radial increment and BAI derived from data in Meyer (1929) compared with present-day values for red spruce in five regions.

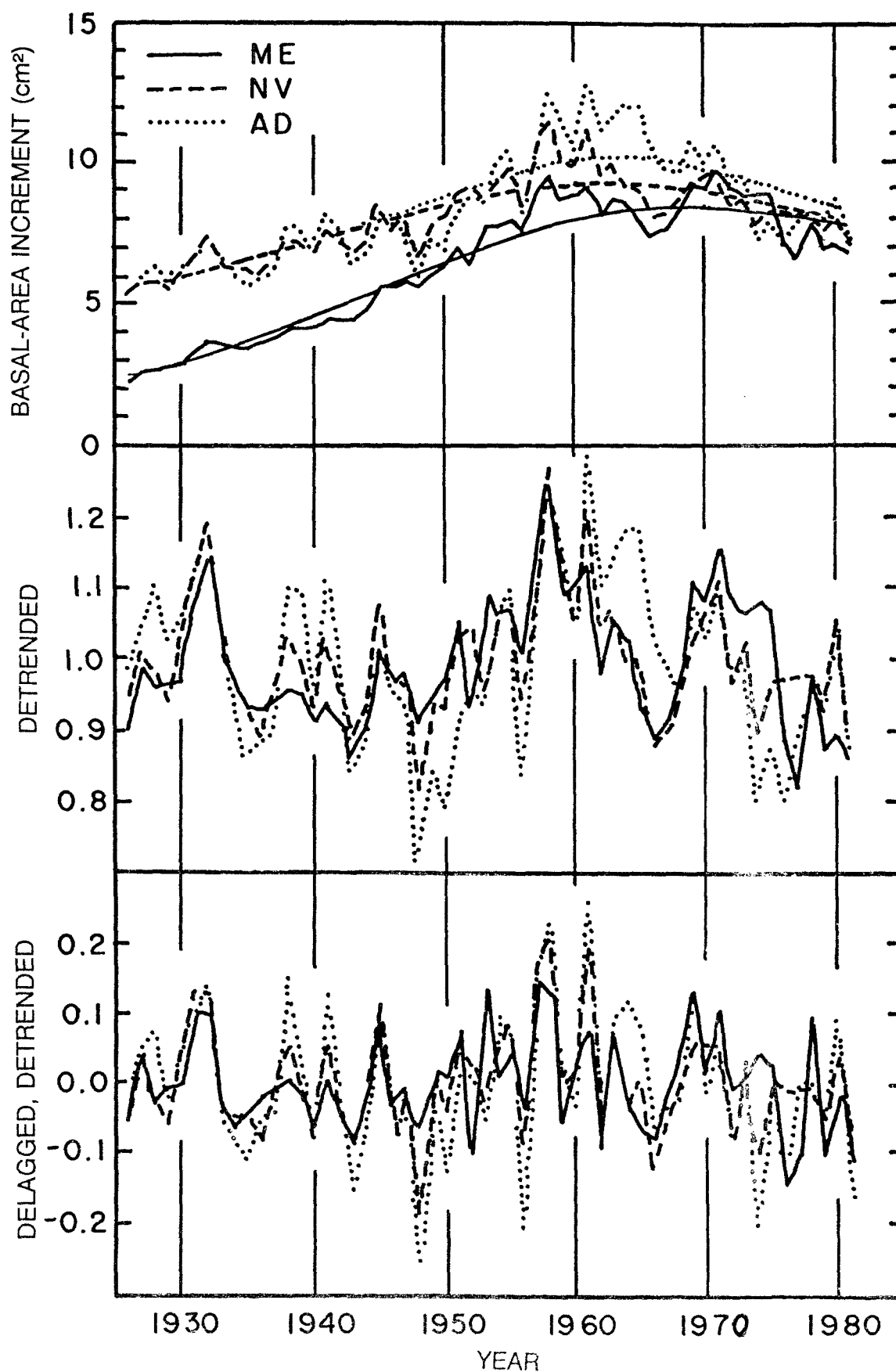


Figure 10.—Time series of BAI for red spruce in three regions. (top) raw series and cubic smoothing spline, (middle) detrended series of raw value/splined value, (bottom) delagged, detrended series, or residuals of AR (1) model fitted to the detrended series.

Table 7.—Results of multiple regression analyses by region using independent variables defined below, with detrended, delagged, regional mean BAI as the dependent variable, 1927–81 (n = 55); these final models include those variables that were significant in one or more regions; F-values are in parentheses; values greater than 4.0 indicate significance at the 95-percent level

Region	r ²	Intercept	Coefficient and variable		
Percent					
MODEL I					
ME	18	−0.086	−0.004 pJAT (0.13)	+0.018 WT (6.60)	+0.017 ST (4.31)
NV	29	0.285	−0.029 pJAT (11.55)	+0.012 WT (3.39)	+0.022 ST (6.17)
AD	33	0.687	−0.047 pJAT (17.63)	+0.014 WT (3.59)	+0.020 ST (3.72)
MODEL II					
ME	1	0.074	−0.007 pLDD (0.25)		
NV	7	0.315	−0.027 pLDD (3.96)		
AD	14	0.581	−0.049 pLDD (8.87)		
MODEL III					
ME	3	−0.074	−0.002 pLRs (0.14)	+0.011 WRs (1.70)	
NV	14	0.181	−0.009 pLRs (3.29)	+0.013 WRs (5.32)	
AD	17	0.630	−0.020 pLRs (9.15)	+0.008 WRs (1.14)	

pJAT = previous July–August temperature; WT = previous Nov–Dec–Jan temperature; ST = September temperature; pLDD = previous late season degree days; pLRs = previous late season respiration; WRs = winter respiration.

Of the 15 trees sampled, 1 tree died in the 1950's, 2 died in the 1960's, 6 died in the 1970's, and 6 died in the 1980's (Table 9). The breast-height age of these trees ranged from 133 to 321 years and diameters ranged from 18 to 52 cm. On the basis of tree ages and diameters, the stand appears to be old-growth, not subjected to prior harvest. Annual BAI growth in these trees fell roughly into three categories (Fig. 11). Eight trees had slow growth rates that were less than 5 cm² yr^{–1} since 1850. Three trees grew at intermediate rates and had extended periods of growth of 5 to 10 cm² yr^{–1} since 1850. The four fast-growing trees had growth rates as high as 35 cm² yr^{–1}. The fast-growth trees had an average diameter of 44 cm compared to 33 and 24 cm for intermediate and slow-growth trees, respectively.

Trees in the fast growth-rate class exhibited two periods when slowing growth was followed by a 30- to 40-year period of higher relatively constant growth (Fig. 12). A 66 percent drop in growth from 1870 to 1872 was followed by a long period of relatively constant growth that was higher than pre-1870 levels. A second decrease around 1920 was followed by subsequent growth rates that fluctuated at a higher level until 1958. Growth rates in all four trees fell an average of 47 percent from 1958 to 1960. The largest tree, 52 cm d.b.h., had a steep linear decrease in growth from 1960 until 1984 when it died. Two other trees had steep linear growth decreases for 10 years from 1960 to 1970 and then 9 to 11 years of less steeply decreasing growth rates until their deaths. The remaining tree had a steep linear

Table 8.—Rotated factor pattern from factor analysis

Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
MEANBAI	0.85	0.06	0.10	0.23	0.10
BA-MID	0.83	0.06	0.04	-0.28	-0.07
PLOT-BA	0.04	0.77	-0.15	-0.03	-0.10
HARVEST	-0.04	-0.50	0.02	0.04	-0.08
DRY	0.02	-0.05	0.70	0.04	0.09
DEPTH	-0.06	0.16	-0.41	-0.04	-0.14
SHAL-ROOT	-0.03	-0.02	-0.42	0.02	0.18
LINEAR	-0.02	-0.08	0.06	0.86	-0.08
ELEVATION	-0.05	0.00	-0.07	0.01	0.42
SAND	-0.03	0.06	-0.06	-0.02	-0.30
CURVATURE	-0.03	-0.09	-0.02	0.09	-0.34

growth decline from 1971 to 1982.

The period of decreasing growth preceding the death of individuals in the slow- and intermediate-growth classes is approximately half of the 20-year period for the high-growth trees (Fig. 11). The 1958-60 growth decrease signaled the start of the decline in the fast-growing trees. Intermediate-growth trees were able to maintain pre-1958 rates through the 1960's even though they had a similar percentage decrease in growth as the fast-growth trees for the 1958-60 period. The slow-growth trees had a 62 percent decrease for this period. Four of the eight trees in this class had a marked decrease in 1958-60 while three other trees had minimal growth for 10 to 15 years preceding this period. Graphing individual trees indicated that most trees in the two slower growth classes experienced similar declines earlier in their lives from which they were able to recover. These earlier events, including the growth decreases occurring around 1870, probably included the death of competitors. Weiss et al. (1985) reported that numerous red spruce in northern New England and the Adirondacks were killed by the spruce beetle (*Dendroctonus rufipennis* Kirby) during the 1870's. The beetles may have been responding to conditions similar to those leading to the current rates of mortality.

The second study entailed collecting increment cores at

breast height from trees that died between 1986 and 1987 surveys of permanent plots located in three states. The sample consisted of 16 dominant trees, 54 to 128 years old, growing at elevations of 700 to 1,000 m. Diameters ranged from 10 to 27 cm. The dead trees represented an average of 3 percent of the total trees on a plot. The general growth patterns discussed for the Mt. Washington sample are repeated for trees located in New Hampshire, New York, and Vermont (Fig. 13). Faster growing trees have the longest and steepest changes in growth compared to slower growing trees, which tend to grow at steadier rates.

In the early to mid-1960's, growth rates began to decrease from an average of 5 cm² yr⁻¹ for trees in New Hampshire and New York. The faster growing trees had nearly linear declines lasting 10 to 15 years while slower growing trees had steep growth drops occurring over 3 to 4 years followed by constant growth at a lower plateau. Sample trees from Vermont with growth rates of 1 to 2 cm² yr⁻¹ tended to grow slower than trees from the other states, and showed a reduction in growth from 1969 to 1974. Growth was relatively stable at these lower rates until death. The timespan covered by decreasing growth increment for most of these dead trees indicates that processes affecting mortality are accumulated over 2 to 3 decades.

Discussion

Our study was conducted as part of the Forest Response Program, a national research effort for addressing concerns about impacts of atmospheric pollutants on forest health (Schroeder and Kiester 1989). The Program includes six cooperatives that have been assigned research questions focusing on three policy issues. The first of these issues, of most concern to our study, asks: Is there a significant problem of forest damage in North America which might be caused by acid rain, its precursors, and associated pollutants? Regarding this issue, the National Vegetation Survey Cooperative, which has funded our research, has been asked to answer two scientific questions:

1. Are changes over time in the condition of forests greater than can be attributed to typical trends and levels of natural variability?
2. What spatial pattern or patterns, if any, exist in forest condition, and how do such patterns relate to spatial patterns of pollutant exposure?

Regarding Question 1, our study suggests that changes in annual growth rates in portions of New England forests represented by our sample are not greater than expected natural variability. Most species grew at constant or increasing rates through the 1970's, with year-to-year variation explainable by weather variation and insect outbreaks. Only in red spruce and balsam fir has there been a generally decreasing growth rate of trees throughout the region. This decrease began around 1960 and coincides with expectations for an even-aged forest regenerated in the early part of the century.

We stress that most of our sampled red spruce were growing at elevations below 1,000 m, in what is commonly called the commercial spruce-fir forest. The age of this forest has been strongly structured by past cutting and budworm outbreaks, adding plausibility to the theory of common maturation. The picture is less clear for red spruce at higher elevations, and in New York, where ages are more variable and generally older. Our sample chronologies from individual dead trees on Mt. Washington indicate that previous periods of decreasing growth rates, similar to the 1958-60 decrease that led to the death of these trees, have occurred in the past and are not unusual in high-elevation, old-growth forests. Van Deusen (1987) suggests that old-growth red spruce at higher elevations do not show a consistent decrease in growth rates compared with our second-growth low-elevation red spruce. However, others including Cook et al. (1987), McLaughlin et al. (1987), and Johnson and Siccama (1984) suggest that growth rates at high elevations (more than 1,000 m) have been decreasing since around 1960 in combination with unusual foliar symptoms and increased mortality.

We have argued that the growth decrease at low elevations and the mortality at high elevations could have two separate causes. But the synchrony of maximum growth around 1960

followed by a decrease in growth or mortality in both low and high-elevation trees throughout the Northeast, suggest that a common cause is possible. A series of abnormal weather periods has been suggested as that cause (McLaughlin et al. 1987). Loss of foliage from winter injury and lack of carbohydrate storage over winter have been suggested. However, such weather-induced effects have been neither well quantified regionally nor explained physiologically. There is considerable unexplained state-to-state covariance in ring widths, so undescribed regional weather effects do exist. Such effects could both have induced a 20-year slide into mortality of old, high-elevation trees, and have synchronized the years of maximum growth in a generally even-aged low-elevation population.

The often stated argument that high-elevation mortality is related to high levels of air pollution does not explain the 1960 synchrony at low and high elevations. Shortle and Smith (1988) suggest that a possible explanation for growth

Table 9.—Characteristics of dead trees from Mt. Washington

Last year of growth at BH	Age at last year of growth	Diameter	Growth rate
	<i>Years</i>	<i>cm</i>	
1957	160	23	slow
1964	133	22	slow
1968	321	32	slow
1973	312	27	slow
1973	248	38	intermediate
1973	159	18	slow
1978	212	22	slow
1978	156	19	slow
1979	208	45	fast
1981	222	41	fast
1982	292	35	intermediate
1982	162	27	slow
1982	161	22	intermediate
1984	253	52	fast
1984	233	39	fast

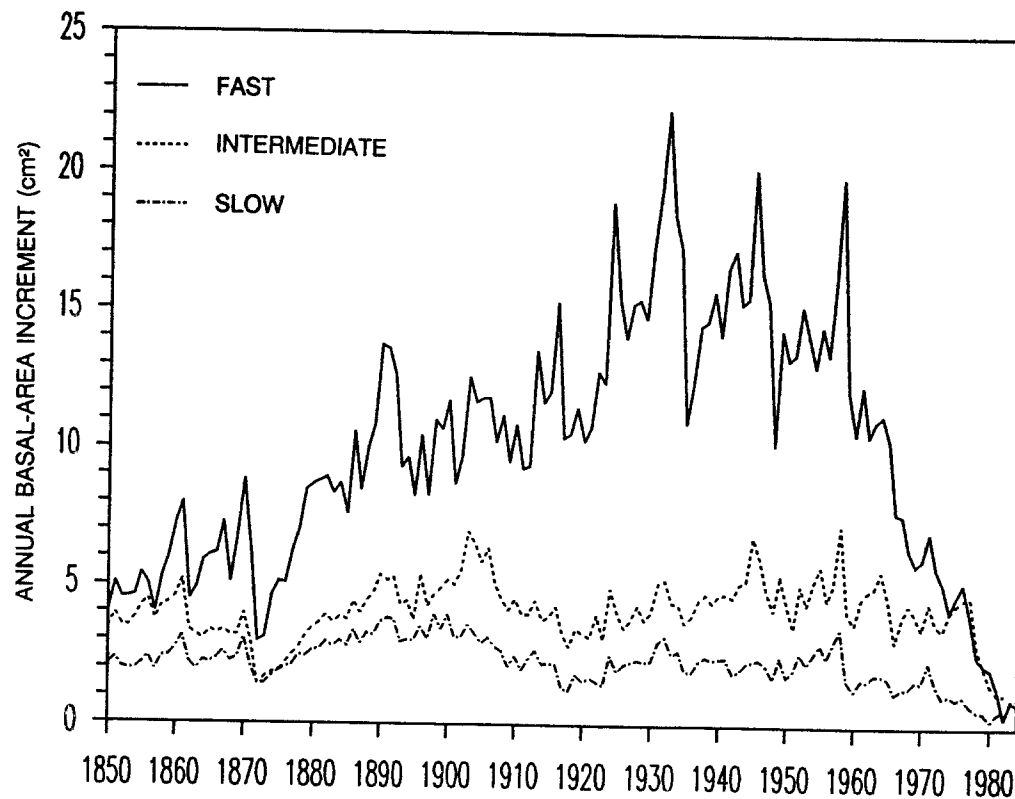


Figure 11.—Mean annual BAI from dead trees that grew at three different rates on Mt. Washington.

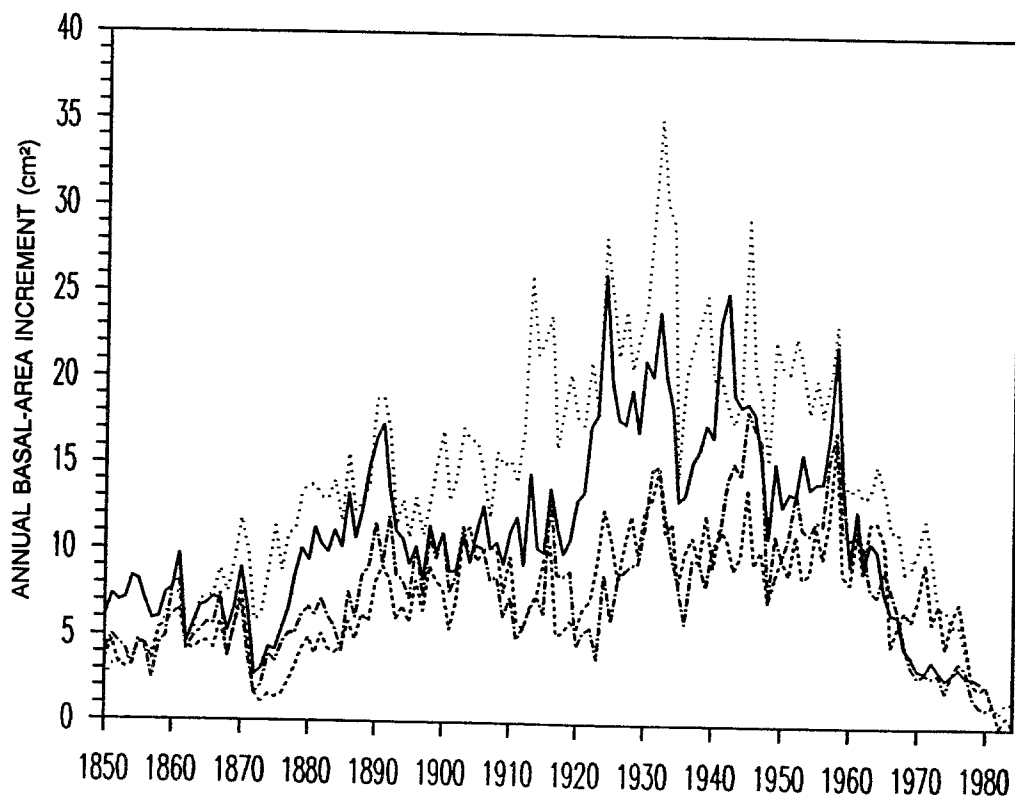


Figure 12.—BAI for individual dead trees that grew at fast rates on Mt. Washington.

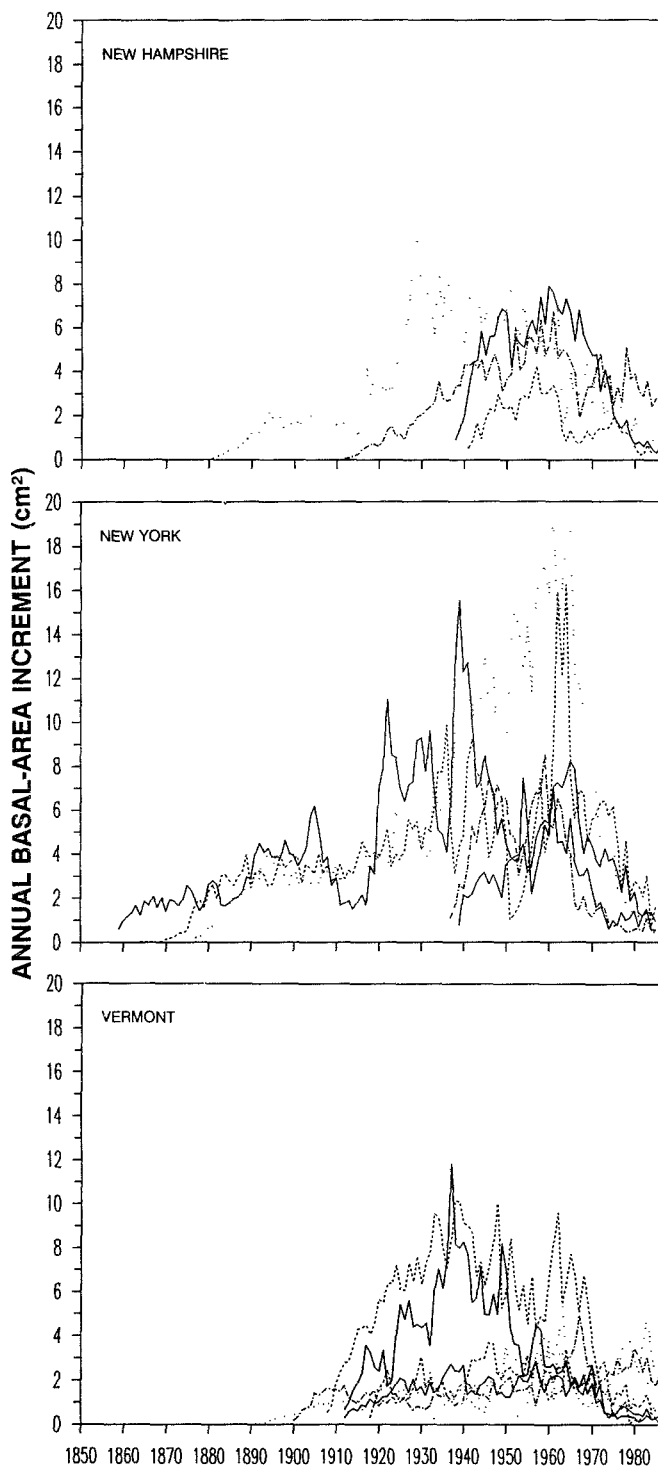


Figure 13.—BAI for individual dead red spruce trees that grew in New Hampshire, New York, and Vermont.

decreases and mortality of red spruce at high elevations is that acid precipitation on shallow, unfertile soils disrupts the balance between soluble calcium and aluminum. An increase in aluminum is then thought to inhibit uptake of calcium, resulting in reduced crown and declining vigor. However, this and other arguments for high-elevation pollution do not explain the synchrony with low-elevation growth patterns.

Balsam fir was the only other species showing a recent, extended period of decreasing growth rates. It has not suffered the same high-elevation mortality as red spruce. Maturation of the low-elevation forest may be an adequate explanation (Hornbeck et al. 1986). The other eight species we studied, which together with red spruce and balsam fir make up 86 percent of New England forests, showed either level or increasing growth rates since 1950 (Fig. 4). The species included sugar maple, which did not show any indication of the decline that is of present concern in the province of Quebec (McLaughlin et al. 1985), and white pine, which is particularly susceptible to air pollution (Gerhold 1977). In short, none of the 10 major species examined showed trends or levels of growth that appear to be outside ranges explainable by natural variation.

With regard to Question 2 about spatial patterns, there is a pronounced gradient in acid deposition across New England, with heaviest levels in western and southern sections, gradually decreasing when progressing to the north and east (Nat. Atmos. Deposition Prog. 1988). The growth data we developed from tree rings did not show a relationship with this gradient. Growth patterns for individual species were consistent regardless of location.

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Appendix

Description of Data Files

Individual-tree ages ranged from less than 20 to more than 300 years. Early growth data from the very old trees was not critical to our analysis of growth of present-day forests. Thus, data storage requirements were reduced by storing only the measurements from 1850, termed "1850" files, after the data were converted from raw ring widths to annual BAI. Measurements predating 1850 were retained in the original files generated by the measuring device.

The 1850 files consisted of alternating decades of annual BAI and raw ring widths from 1850 through 1985 for each tree (Table 10), along with a header record containing a tree's plot number, tree number, species code, county,

state, age, estimated years to pith, measurer's initials, measurement date, file type, bark thickness, d.b.h. inside bark, d.b.h. in 1850, and a variable indicating whether or not the core struck the pith.

A record for each tree was entered into a separate plot-level file containing physical site characteristics and growth indices (Table 11). Plot files and 1850 files were linked by plot number, tree number, county number, and state code. Important plot characteristics selected for this file included harvest history, elevation, depth of organic layer, rooting depth, soil texture, parent material, moisture class, soil series, and total-plot basal area. Individual-tree growth indicators could be added to the plot-level files at any time, allowing the exploration of relationships between growth and site characteristics. Both the 1850 and plot-level files are available to the public.

Table 10.—Example of an 1850 file that stores both radial and BAI from individual trees within the same file

PLOT NUMBER	TREE NUMBER	SPECIES CODE	COUNTY CODE	STATE CODE	TREE AGE	ESTIMATED YEARS TO PITH	OPERATOR'S INITIALS	DATE MEASURED	FILE TYPE	BARK THICKNESS	DBH cm	DBH IN 1850	PITH CHARACTER
41	97	323	561	MCK	82984	AC	5.19	20.63	0.00	1			
1850	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	DECADE OF BAI (SQ. CM)
1850	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	DECADE OF RADIAL INCREMENTS (MM)
1860	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	DECADE OF BAI
1860	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	DECADE OF RADIAL INCREMENTS
1870	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***
1870	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***
1880	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***
1880	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***
1890	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***
1890	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***
1900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***
1900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***
1910	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***
1910	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***
1920	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.69	0.81	0.96	1.16	***
1920	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.96	3.12	2.10	1.89	1.85	***
1930	1.70	2.08	2.01	1.61	1.69	2.02	2.44	2.45	2.42	2.59	***		
1930	2.25	2.31	1.94	1.41	1.38	1.53	1.72	1.61	1.49	1.51	***		
1940	2.88	2.92	2.66	2.96	3.18	3.59	3.03	3.68	4.81	5.52	***		
1940	1.59	1.53	1.33	1.42	1.46	1.58	1.28	1.50	1.88	2.06	***		
1950	6.80	4.84	6.60	4.74	5.28	6.20	7.02	7.30	7.14	8.23	***		
1950	2.41	1.64	2.15	1.49	1.61	1.83	2.00	2.01	1.90	2.12	***		
1960	6.60	6.07	6.76	7.92	5.95	6.88	7.21	8.08	12.52	11.97	***		
1960	1.65	1.48	1.61	1.84	1.35	1.53	1.57	1.72	2.59	2.40	***		
1970	15.84	15.84	12.07	15.99	12.29	9.86	8.09	12.41	8.00	10.97	***		
1970	3.07	2.96	2.19	2.82	2.11	1.66	1.34	2.02	1.28	1.73	***		
1980	8.88	0.00	0.00	0.00	0.00	0.00							BAI VALUES THROUGH 1985
1980	1.38	0.00	0.00	0.00	0.00	0.00							RADIAL INCREMENTS THROUGH 1985
42	97	323	742	MCK	82984	AC	4.37	22.34	0.00	1			
1850	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
1850	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
1860	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
1860	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
1870	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
1870	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
1880	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
1880	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
1890	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
1890	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
1900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.12	1.16		
1900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.94	4.44		

Table 11.—Example of a plot-level file linking individual-tree measurements with site information

PLOT NUMBER	TREE NUMBER	SPECIES CODE	COUNTY CODE	STATE CODE	TREE AGE	ESTIMATED YEARS TO PITH	FILE TYPE	DBH cm	SIGN. RI & BAI SLOPE 1940-59	RI SLOPE 1940-59	SIGN. RI SLOPE 1940-59	BAI SLOPE 1940-59	SIGN. BAI SLOPE 1940-59	SIGN. RI & BAI SLOPE 1960-8	RI SLOPE 1960-8	SIGN. RI SLOPE 1960-8	BAI SLOPE 1960-8	SIGN. BAI SLOPE 1960-8	PI CLASS	OWNER CLASS	FOREST TYPE	PLOT ORIGIN	HARVEST HISTORY	SURFACE BOULDER CLASS	WATER ON PLOT	ELEVATION	DEPTH OF ORGANIC LAYER	ROOTING DEPTH	DEPTH TO MOTTLING	TEXTURE OF B HORIZON	DEPTH TO BEDROCK	PARENT MATERIAL	MOISTURE CLASS	SOIL SERIES	TREE HEIGHT	SITE INDEX	STAND SIZE	TOTAL PLOT BASAL AREA	BASAL AREA 5'+ DBH
142	97	523	393AC	16.81	3	0.005	0	0.270	1	0	0.028	0	0.387	0	26	41	3	-9	3	1	-9	1	25	1	0	2	4	1	3	34	43	5	-9	-9	-9				
1221	97	523	1362NG	21.58	4	0.037	1	0.249	1	2	-0.065	1	-0.345	1	22	38	13	1	3	0	0	0	20	1	0	1	4	3	4	76	59	5	3	97	45				
1222	97	523	1800NG	16.45	0	0.004	0	0.020	0	0	0.010	0	0.056	0	22	38	13	1	3	0	0	0	20	1	0	1	4	3	4	76	59	5	3	97	45				
1223	97	523	1463NG	21.01	0	-0.007	0	0.004	0	2	-0.006	1	-0.029	1	22	38	13	1	3	0	0	0	20	1	0	1	4	3	4	76	61	5	3	97	45				
1224	97	523	1543NG	18.43	1	-0.017	0	0.064	1	0	-0.012	0	-0.062	0	22	38	13	1	3	0	0	0	20	1	0	1	4	3	4	76	61	5	3	97	45				
1861	97	523	1152NG	29.34	3	0.015	0	0.035	1	2	-0.023	1	-0.120	1	24	40	5	1	0	1	5	4	25	2	0	2	4	2	3	6	55	5	1	155	115				
1862	97	523	663NG	17.36	3	0.000	0	0.081	1	0	-0.020	0	-0.033	0	24	40	5	1	0	1	5	4	25	2	0	2	4	2	3	6	55	5	1	155	115				
1863	97	523	802NG	18.71	1	0.028	0	-0.085	1	3	-0.003	1	0.116	1	24	40	5	1	0	1	5	4	25	2	0	2	4	2	3	6	55	5	1	155	115				
1864	97	523	703NG	22.31	1	-0.024	1	-0.016	0	0	-0.033	0	-0.118	0	24	40	5	1	0	1	5	4	25	2	0	2	4	2	3	6	55	5	1	155	115				
71	97	723	491AC	19.29	4	0.054	1	-0.296	1	0	-0.012	0	0.278	0	22	29	11	-9	0	0	-9	10	25	1	9	3	4	1	4	3	41	6	-9	-9	-9				
503	97	723	1102AC	24.42	3	0.007	0	0.266	1	2	-0.053	1	-0.326	1	23	29	81	-9	0	0	-9	15	35	2	0	3	4	1	3	25	62	5	-9	-9	-9				
504	97	723	753AC	29.59	2	-0.115	1	-0.277	1	0	-0.063	0	-0.467	0	23	29	81	-9	0	0	-9	15	35	2	0	3	4	1	3	25	68	5	-9	-9	-9				
612	97	723	1342AC	21.66	4	0.039	1	0.260	1	0	0.007	0	0.150	0	24	29	13	-9	0	0	-9	15	35	2	0	3	4	1	3	25	56	5	-9	-9	-9				
614	97	723	660AC	19.62	4	0.028	1	0.284	1	3	-0.013	1	0.173	1	24	29	13	-9	0	0	-9	15	35	2	0	3	4	1	3	25	55	5	-9	-9	-9				
861	97	723	413AC	22.16	3	-0.084	1	0.435	1	4	0.010	1	0.360	1	25	29	13	-9	0	2	-9	21	0	1	0	4	4	1	3	20	49	5	-9	-9	-9				
862	97	723	472AC	15.25	4	0.027	1	0.235	1	0	-0.002	0	0.147	0	25	29	13	-9	0	2	-9	21	0	1	0	4	4	1	3	20	46	5	-9	-9	-9				
863	97	723	434AC	22.75	3	-0.077	1	0.399	1	3	-0.044	1	0.109	1	25	29	13	-9	0	2	-9	21	0	1	0	4	4	1	3	20	49	5	-9	-9	-9				
864	97	723	532AC	23.81	3	-0.009	0	0.594	1	0	-0.104	0	-0.514	0	25	29	13	-9	0	2	-9	21	0	1	0	4	4	1	3	20	57	5	-9	-9	-9				
961	97	723	852AC	19.29	4	0.067	1	0.347	1	0	0.022	0	0.273	0	23	15	11	-9	3	0	-9	17	30	2	0	3	2	1	3	6	47	5	-9	-9	-9				
963	97	723	574AC	21.25	3	-0.019	1	0.181	1	0	0.015	0	0.204	0	23	15	11	-9	3	0	-9	17	30	2	0	3	2	1	3	6	51	5	-9	-9	-9				

Smith, Robert B.; Hornbeck, James W.; Federer, C. Anthony; Krusic, Paul J., Jr.
1990. **Regionally averaged diameter growth in New England forests.**
Res. Pap. NE-637. Radnor, PA: U.S. Department of Agriculture, Forest
Service, Northeastern Forest Experiment Station. 26 p.

A regional sample of tree-ring measurements was used to determine average annual growth in trees of 10 major species in New England. There have been extended periods of decreasing growth rates in red spruce since about 1960 and in balsam fir since about 1965. The other eight species, which included sugar maple and white pine, showed constant or increasing growth rates through 1980. The decreases in growth rate in sampled red spruce and balsam fir were independent of physical site characteristics, elevation, and geographic location, indicating that regional factors are involved. Weather parameters were not closely correlated with growth rates, and the best predictive equation explained only 33 percent of annual variation.

ODC: 181.65 (74)

Keywords: growth decline; growth patterns; red spruce; annual basal-area increment; increment cores; forest maturation; air pollution; regional weather

Headquarters of the Northeastern Forest Experiment Station is in Radnor, Pennsylvania. Field laboratories are maintained at:

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