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A Survey of Radial Growth Trends in Spruce in the Great Smoky Mountains National Park as Influenced by Topography, Age, and Stand Development

H. S. Adams
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T. J. Blasing
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Environmental Sciences Division
Publication No. 3427

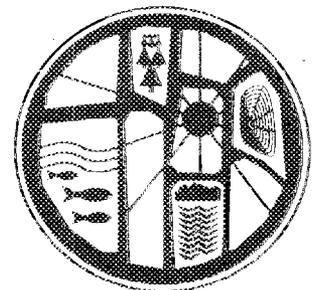
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ENVIRONMENTAL SCIENCES DIVISION

A SURVEY OF RADIAL GROWTH TRENDS IN SPRUCE IN THE
GREAT SMOKY MOUNTAINS NATIONAL PARK AS INFLUENCED
BY TOPOGRAPHY, AGE, AND STAND DEVELOPMENT

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Environmental Sciences Division
Publication No. 3427

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ABSTRACT

ADAMS, H. S., S. B. MCLAUGHLIN, T. J. BLASING, and D. N. DUVICK. 1989. A survey of radial growth trends in spruce in the Great Smoky Mountains National Park as influenced by topography, age, and stand development. ORNL/TM-11424. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 69 pp.

A survey of red spruce growth trends at several sites in the Great Smoky Mountains National Park (GSMNP) was undertaken to determine the relationship of the magnitude and timing of changes in annual radial increment to elevation, aspect, tree age, mortality, and competitive status. Examination of increment cores collected from 15 trees at each of 4 elevations (1385 to 1845 m) on east- and west-facing slopes of Mt. LeConte revealed synchronous reductions in radial growth at the upper elevations typically beginning in the early 1960s or early 1970s. These reductions, which totalled 30-40% over the past 10 years, were greatly diminished or absent at the lowest elevation and were generally most pronounced on east-facing slopes and on older trees. Mortality levels were highest at high elevations (11.4% maximum) and on west slopes, but were substantially below levels reported in upper-elevation northeastern spruce forests. Cores taken from standing dead trees showed a general slowing of radial growth during the past 25 years to levels (0.5-1.0 mm/year) comparable to those noted in currently living high-elevation trees. A stratified sample of trees in three size classes at Mt. Sterling showed the same general timing of growth decline in all size classes, with a recent reversal of that decline in smaller trees [≤ 25 cm diameter at breast height (dbh)]. This response was associated with an apparent competitive release resulting from heavy mortality of Fraser fir during the past 10-15 years. The pattern of growth decline observed in the GSMNP was not consistently related to age of stands, drought, or competitive status of sampled trees. The stocking level of red spruce and two much younger (50-year-old) Norway spruce stands with similar declines was well below the maximum capacity of red spruce. The observed changes in radial growth suggest a larger scale stress of the type affecting red spruce in the Northeast, although

mortality levels at the sites studied in the GSMNP were well below those noted in northeastern stands in previous studies.

The growth changes observed suggest responses to changes in climate (principally temperature) or atmospheric pollution acting individually or, more likely, in combination. Major emphasis on these potential causes is warranted in future studies.

INTRODUCTION

Evidence suggesting that the red spruce in the Appalachians is being adversely affected by as yet unidentified regional scale stress(es) has accumulated rapidly in the past 5 years (McLaughlin 1985; Johnson and McLaughlin 1986). Dendroecological (tree-ring) data from studies conducted in spruce and/or spruce-fir [*Abies balsamea* (L.) Mill. or *Abies fraseri*] forests in the northern and mid Appalachians (Johnson and Siccama 1983a, 1983b; Adams et al. 1985; McLaughlin et al. 1987) indicate that red spruce has exhibited a pattern of reduced radial growth at many sites across the region during the past two decades. Reduced growth has been accompanied by increased mortality in the northern stands. Spruce at several sites in the Northeast showed more decline at higher elevations and on east-facing slopes than at lower elevations or on west-facing slopes (Johnson and Siccama 1983b; Johnson 1983).

In the mid-Appalachian region, spruce and fir are restricted to high-elevation sites and widely scattered locations. Increases in mortality along the southern extension of these forests have been noted principally in Fraser fir [*Abies fraseri* (Pursh)] and have been attributed primarily to increasing attack from the exotic insect pest, the balsam wooly adelgid (*Adelges picea*), which has caused extensive loss of trees in the Great Smoky Mountains of Tennessee and North Carolina (Eagar, 1984).

The exact cause or causes of decline in growth rates for spruce, fir, and some southern pine species in the Southeast during the past two decades (Sheffield and Cost 1987) are still unknown (McLaughlin 1985), although acid deposition and other regional air pollutants have been suggested as possible contributing factors (Johnson and Siccama 1983a, 1983b; Johnson et al. 1981; Puckett 1982; Roman and Raynal 1980; Vogelmann 1982; McLaughlin 1985) based on the occurrence of the affected forests in areas receiving high atmospheric inputs of acidic substances and other pollutants (Cowling 1983; Likens and Butler 1981; McLaughlin et al. 1983). Climate has also been suggested as a contributing factor

to observed growth declines. Johnson and Siccama (1983a) hypothesized that the decline in the Northeast was triggered by a drought that occurred there during the early-to-mid 1960s. Adams et al. (1985) showed limited relationship between decline and drought. Winter damage to foliage possibly associated with enhanced deposition of nitrogen to high-elevation ecosystems has also been suggested as a possible contributing factor in observed-spruce decline in the northeast (Friedland et al. 1985).

Red spruce in the southern Appalachians is restricted to the higher elevation mountain slopes by a warmer climate. In the Great Smoky Mountains in Tennessee and North Carolina, it is a significant component of the spruce forest (elevations 1372 to 1646 m) and of the spruce-fir forest (1676 to 1859 m) and occurs in decreasing proportions with elevation in the fir-dominated forest above 1859 m (see Whittaker 1956 and Appendix A for a more detailed description of the ecology of red spruce in this area). The decline of red spruce in the southern Appalachians is of particular interest because its limited elevational range and the presence of historically lower levels of atmospheric emissions in the South provided an experimental setting in which to examine both natural and emission-related gradients.

In our earlier work in this area, measurements from red spruce cores obtained at two sites in the Smokies (McLaughlin et al. 1983) exhibited substantial differences in recent growth trends. At Mt. Collins, a growth-trend decline commencing in the late 1960s was followed by recovery during the mid-1970s, but then continued again after 1979. In contrast, cores from Indian Gap exhibited continuous decline since the early 1960s. Cores collected from red spruce at various sites in the eastern half of the Smokies also showed a growth-trend decline beginning in the early 1960s (unpublished data, H. S. Adams, R. D. Rheinhardt, and M. L. Lipford). On nearby Mt. Mitchell in North Carolina, approximately 75 km east of the GSMNP, Bruck (1984) indicated that red spruce above 1935 m elevation was in a severe state of decline, with all trees exhibiting a marked reduction in growth beginning in the early 1960s, although trees at lower elevations did not display increment suppression.

As a result of these earlier findings, an exploratory survey was initiated to better establish the extent of red spruce decline in a limited area of the Great Smoky Mountains National Park. This study was designed to (1) determine the influence of elevation and aspect on observed growth trends and associated mortality of red spruce and compare these trends with those observed from similar gradient studies from the North (Johnson and Siccama, 1983a); (2) determine growth trends prior to the mortality of red spruce to determine if growth for the few years prior to death was distinctively different from earlier growth; (3) assess the relationships between decline and stand competition [this was approached by examining growth trends in relation to size and/or age class by collecting cores from three size classes of red spruce in a mixed size/age stand in which Fraser fir had been eliminated recently by the balsam woolly aphid (see Appendix A)]; and (4) evaluate growth decline in planted Norway spruce [*Picea abies* (L.) Karst.] at two elevations to evaluate growth patterns in this species, which has been shown to exhibit severe decline and dieback in several European and Scandinavian countries (FRG 1984).

METHODS

MT. LECONTE SURVEY

Eight sampling sites were selected along major trail systems on 7.5-min U.S. Geological Survey (USGS) quadrangle maps and located as accurately as possible in the field. Sites were chosen to represent the major range of elevation occupied by red spruce (approximately 1375 to 1875 m) on each of two major exposures (northeast and southwest). Teflon-coated, steel increment borers (45.7 cm long, 5 mm diam) were used to extract two 5-mm-long cores at breast height (1.4 m above ground level) from each of 15 red spruce trees in dominant or codominant crown classes at 4 elevations on each exposure. Cores were taken parallel to the slope and opposite one another if possible (but never closer than 90°). The diameter of each tree (1.4 m above ground level) was recorded, and a subjective evaluation of its vigor status based on foliage loss was made using a scale outlined by Bucher and Mahrer (1983). Scale values were: 0 (sound, no evidence of needle loss or damage), 1 (sickly, but damage to less than half the foliage), 2 (damage evident in 50-75% of the foliage), 3 (damage to foliage greater than 75% but tree still living), and 4 (tree dead). The basal area (BA) of living and dead trees of each species surrounding the cored individual was estimated as an index of stand competition using a Bitterlich prism (metric 2.5). Prism data for all cored individuals at each site were collected to establish composition and basal area contribution of each tree species. Vigor status (0-4) of each red spruce tree within the prism was evaluated. Aspect and slope inclination also were recorded at each cored tree. At the highest and lowest elevations for each aspect (northeast and southwest), species, distance, azimuth, and dbh were recorded for the closest living dominant or codominant competitor in each of the four quadrants around each cored tree.

Increment cores were transported to the laboratory in coded plastic tubes where they were air-dried, mounted on grooved boards, and surfaced for measurement. Individual cores were examined to determine date of pith or innermost ring and to subjectively establish the date of any recent (since 1950) transition to unusually narrow growth increments.

Tree ages were estimated conservatively since consideration was not given to years of tree growth prior to attaining coring height or number of rings not observed when pith was not reached. Ring widths (1900-1983) were measured at Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee. Measurements of all cores at each site (30) were grouped, and a robust estimate of mean ring width, the biweight mean (Mosteller and Tukey 1977), was calculated. In calculating the biweight mean, values are weighted such that those most distant from the median receive smaller weights according to criteria given by Mosteller and Tukey (1977). The influence of occasional outlier values is thereby reduced in calculating the mean ring width for a stand.

Site chronologies were then developed by fitting a spline function to the series of measured values for each core, dividing by the spline value to obtain a series of ring-width indices, and averaging the indices of all cores at each site (Cook and Peters 1981; Fritts 1976). This indexing procedure, developed by dendroclimatologists, removes natural low-frequency variations (e.g., those due to tree senescence and/or gradual changes in competitive status) from the ring-width series of individual trees. The resulting ring-width chronology, therefore, represents aspects of ring-width variance that are replicated over several trees in a stand while the influences of stochastic natural processes influencing individual trees in an asynchronous fashion are minimized. Theoretically, a chronology allows comparison of expected growth rates at a site (standardized to a uniform mean value of 1.0) with the measured growth rates (the plotted values). Values less than 1.0 represent years for which the growth rate was less than what would have been expected, and values greater than 1.0 represent years for which the growth rate was more than what would have been expected. Only very strong and abrupt shifts in low-frequency variance are reflected in the resulting index values. By contrast, high-frequency variance typical of year-to-year variability in climate is preserved within the chronology.

As a second approach to standardizing observed growth patterns, recent growth (1972-1981 mean) was compared to prior growth (1932-1961) of the same trees at that site, and percentage of growth change for the

two periods was calculated. The earlier interval was considered a reference period during which atmospheric SO_x , NO_x , and ozone were at much lower levels than during the 1972-1981 decade. Comparisons were also made using the 1952-1961 decade as a reference period; this was the last decade before emissions of sulfur and nitrogen oxides increased sharply in the South (Gschwandtner et. al 1984) and preceded the initiation of most observed declines in radial growth. Statistical procedures other than those already described were performed at Dabney S. Lancaster Community College using Statpak (Gordon 1977), Keystat, or the Statistical Analysis System (SAS) (1982).

DEAD RED SPRUCE SURVEY

Two cores were extracted from each of ten dead red spruce trees to examine the rate of growth decline prior to mortality. Since the bark of most trees was still intact, they were presumed to have died within the past 2 to 5 years. These trees were sampled in three locations: Mt. Collins (near the Appalachian Trail shelter), the west slope of Mt. LeConte, and near Indian Gap. For the Mt. LeConte study, all data were collected as described for the highest and lowest elevations. Annual rings were measured and mean ring widths and indices calculated for the last 50 years of growth. Age at death was determined by counting annual rings to pith or innermost observable annual ring. Attempts to cross-date cores with living specimens were not successful, making it impossible to accurately determine year of death.

MT. STERLING SIZE/AGE CLASS SURVEY

For the size class survey, Mt. Sterling was selected because all size classes of red spruce were known to be present, and this was the first region of the Smokies to be affected by the balsam woolly aphid. Therefore, nearly all Fraser fir, except for saplings and seedlings, were dead. In some areas, the dead fir had been cut and removed; elsewhere it had been left undisturbed. Except for a few of the largest trees, all cores were taken from trees in the undisturbed region. Fifteen red spruce trees in each of three size classes (10-25 cm dbh, >25-40 cm dbh, and >40 cm dbh) were cored. Prism data were not

recorded, but distance, azimuth, and dbh of the four closest competitors (living or recently dead) were determined. Bitterlich prism counts were made around every third cored tree in the middle size class and around each tree in the largest size class. All individuals within the prism, living or dead, were tallied by species. Aspect and slope inclination were recorded for all cored trees. Mean ring widths and indices were developed for each size class from the innermost ring or pith of each core through 1983. The 45 cored trees (2 cores each) also were categorized by age to observe any possible relationships of this variable with growth-trend declines.

NORWAY SPRUCE SURVEY

Two cores were obtained from each of 15 Norway spruce from each of 2 stands planted by Champion Fiber Company in the early 1940s just prior to the establishment of the national park (Chris Eagar, National Park Service, personal communication). The dbh was measured, and vigor status of each tree was estimated at two elevations (1485 m and 1325 m) along the Grassy Branch Trail between Mt. Ambler and Richland Mountain. Bitterlich prism tallies by species were made around every other cored individual in order to estimate competition and establish the composition of the tree stratum. Aspect and inclination of slope were recorded for each cored individual. For each elevation, mean ring widths and indices were calculated based on the innermost ring or pith of each core through 1983.

DESCRIPTION OF STUDY SITES

The site description, elevation, and species sampled at Mt. LeConte, Mt. Sterling, Indian Gap, and Mt. Collins are summarized in Table B-1. Additional details on sampling location, stand characteristics, and species composition at each site are included in Tables B-2, and B-3.

RESULTS AND DISCUSSION

MT. LECONTE SURVEY

Plots of biweight mean radial growth of red spruce at four elevations on each of the southwest and northeast slopes of Mt. Leconte are shown in Figs. 1 and 2, respectively. Site characteristics, stand basal area, dbh, age, growth-trend data of cored trees, and vigor ratings of all trees at each of the eight sample locations are summarized in Table 1.

The mean data in Figs. 1 and 2 show two principal periods of synchronous growth response across most of the eight sample locations: a rapid drop and recovery over an approximate 6-year period that occurred at all sites in the early-to-mid 1950s and a more sustained downward trend beginning around 1965 and continuing through the present. The latter growth decline was most pronounced at high elevations and was weak, transient, or lacking at low elevations.

Most reported tree-growth declines have been generally synchronous with severe droughts, and several researchers have hypothesized that these red spruce declines were induced by drought or that there were unidentified stresses acting synergistically with drought (Johnson and Siccama 1983a; Johnson et al. 1981; Scott et al. 1984; Adams et al. 1985; Johnson 1983; Tainter et al. 1984). In the growth trends shown in Figs. 1 and 2, growth suppression of the early-to-mid 1950s is clearly associated with the most severe drought of the past 50 years. The intensity and timing of this drought is shown in Fig. 3, which was the Palmer Drought Severity Index (PDSI) (Palmer 1965). This log-scale index describes the availability of water relative to the moisture storage capacity of soil and evaporative demand. PDSIs (Palmer 1965) have been shown to correlate well with tree-ring widths in the eastern United States (Cook and Jacoby 1977). Monthly PDSIs indicate relative drought conditions for particular local soil characteristics based on a weighted integral of precipitation and evapotranspiration for several months preceding and including the month for which the index is calculated. Indices range from very dry (≤ -4) to very wet ($\geq +4$), with zero considered normal. September values represent cumulative drought

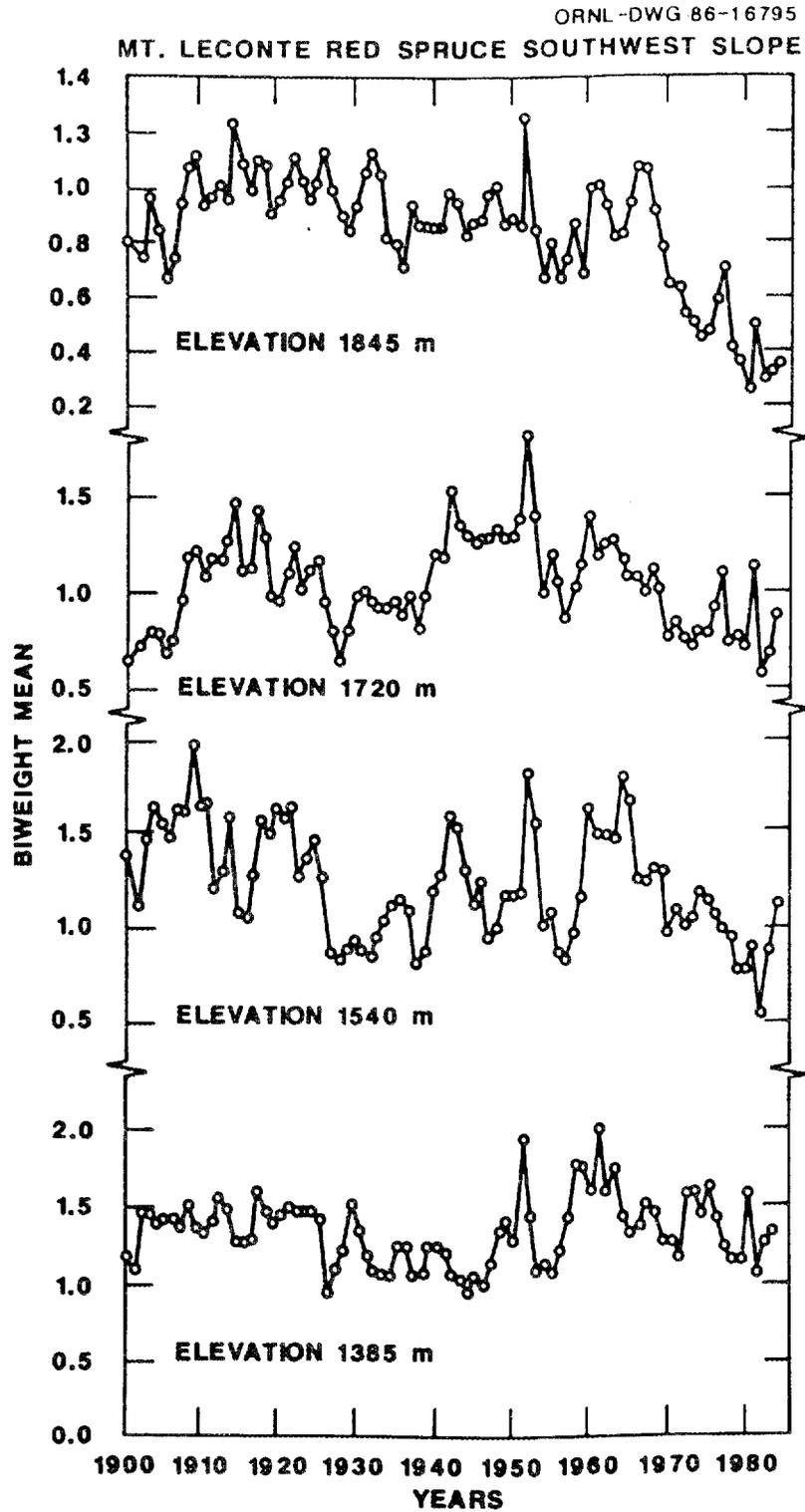


Fig. 1. Biweight mean plots of annual radial growth of 30 increment cores collected from 15 red spruce trees (2 per tree) at each of 4 elevations on the southwest slope of Mt. LeConte.

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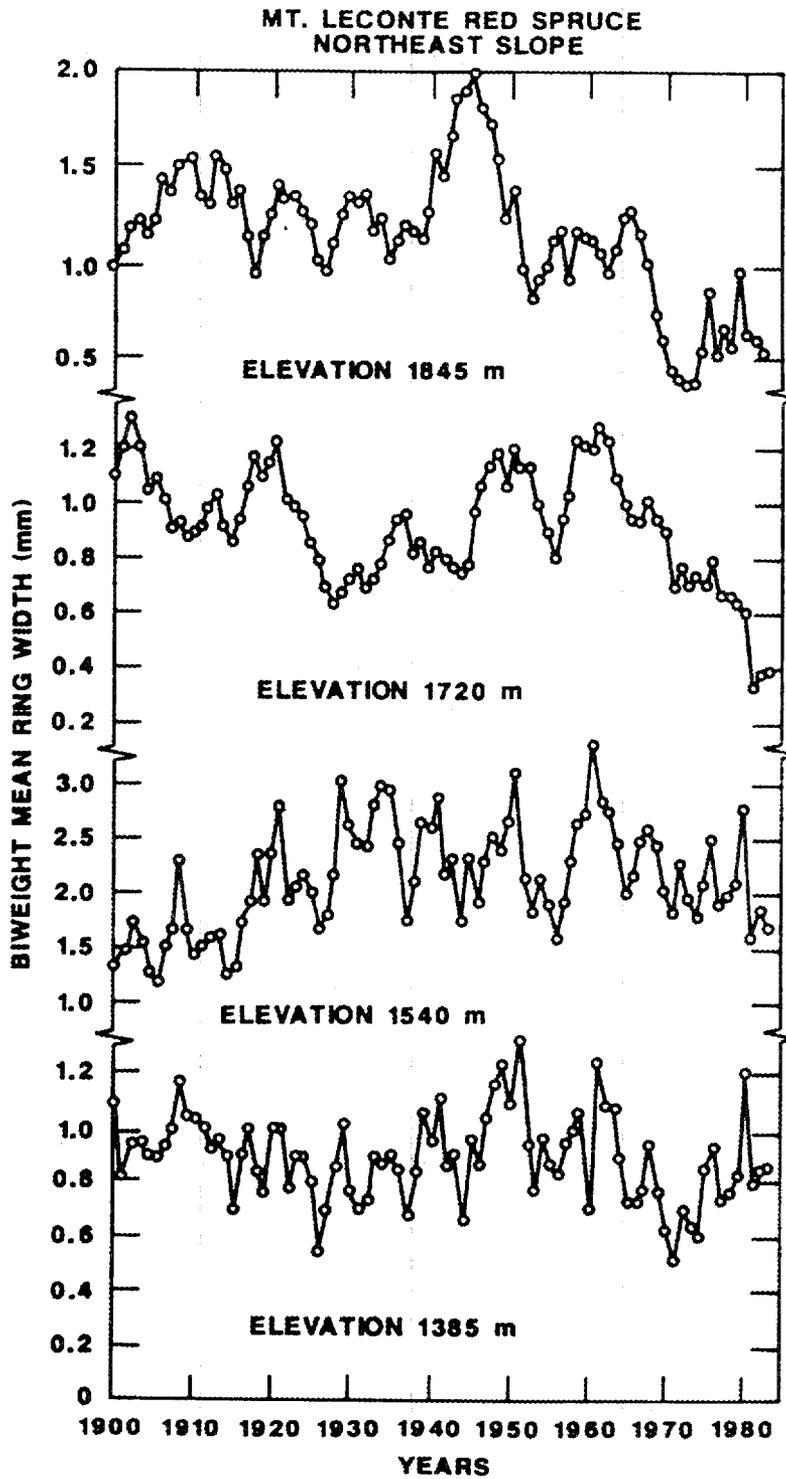


Fig. 2. Biweight mean plots of annual radial growth of 30 increment cores collected from 15 red spruce trees (2 per tree) at each of 4 elevations on the northeast slope of Mt. LeConte.

Table 1. Comparison of variables along east and west elevational gradients on Mt. LeConte, Great Smoky Mountains National Park

	Northeast slope elevation (m) ^a				Southwest slope elevation (m) ^a			
	1385	1540	1720	1845	1385	1540	1720	1845
Site-Specific Aspect (Deg) ^b	79	55	117	130	256	270	228	199
Inclination (%) ^b	59	60	65	80	53	42	50	57
Total basal area (m ² /ha) ^c	42.3	12.8	12.7	50.1	33.5	24.8	41.8	47.2
Live basal area (m ² /ha) ^c	39.5	12.8	11.8	32.3	32.0	22.3	20.8	24.7
Dead basal area (m ² /ha) ^c	2.8	0	0.8	17.8	1.5	2.5	21.0	22.5
Mean dbh of cored trees (cm) (\pm S.E.)	49.2 (3.05)	49.3 (2.32)	50.8 (2.44)	39.6 (2.90)	47.4 (4.16)	61.5 (4.04)	58.6 (3.85)	34.5 (2.08)
Mean age \bar{v} (\pm S.E.) ^d of cored trees (years)	191 (11.0)	110 (7.5)	253 (20.8)	154 (7.1)	148 (14.4)	258 (15.5)	220 (11.2)	193 (8.5)
Percent age of individuals in vigor class ^e :								
0	79.0	84.4	47.9	61.8	71.4	75.0	73.6	75.0
1	11.3	15.6	32.9	30.0	11.4	9.4	10.4	13.5
2	0	0	13.7	6.4	2.9	3.9	1.6	0
3	0	0	0	0	2.9	0	10.4	3.8
4	9.7	0	5.5	1.8	11.4	11.7	4.0	7.7
Percent age of cores showing decline without recovery ^f								
	23.3	0	56.7	53.3	13.3	23.3	36.7	63.3
Percent growth change (1972-1981 compared to 1932-1961) ^g								
	-14.3	-14.0	-32.8	-57.1	+8.3	-21.5	-31.3	-51.8
(1972-1981 compared to 1952-1961) ^g								
	-13.2	-1.8	-24.0	-40.2	+8.1	-7.9	-15.7	-45.5

^aApproximate, based on locations of sample site on 7.5-min U.S. Geological Survey topographic maps.

^bMean of values recorded at each cored tree (\bar{n} = 15 per site).

^cMean of prism (2.5 metric) plots around each cored tree (\bar{n} = 15 per site).

^dBased on mean number of annual rings counted to pith or innermost annual ring observed for each cored tree (\bar{n} = 15 per site); this does not consider possible missed annual rings due to not hitting exact center or growth occurring prior to attaining coring height.

^eSubjective evaluation of foliage loss of all red spruce trees within prism plots using the following rating scale: 0=healthy, no needle loss apparent; 1=obvious loss of vigor with <50% of needles lost; 2=50-75% needle loss; 3=>75% needle loss but tree still alive; and 4=dead.

^fBased on inspection of individual cores for dates of abrupt transition to unusually narrow growth increments (\bar{n} = 30 per site).

^gBased on mean growth of cores during reference period 1932-1961 and mean growth of these same cores during 1972-1981, and mean growth of cores during reference period 1952-1961 and mean growth of these same cores during 1972-1981 (\bar{n} = 30 cores per site).

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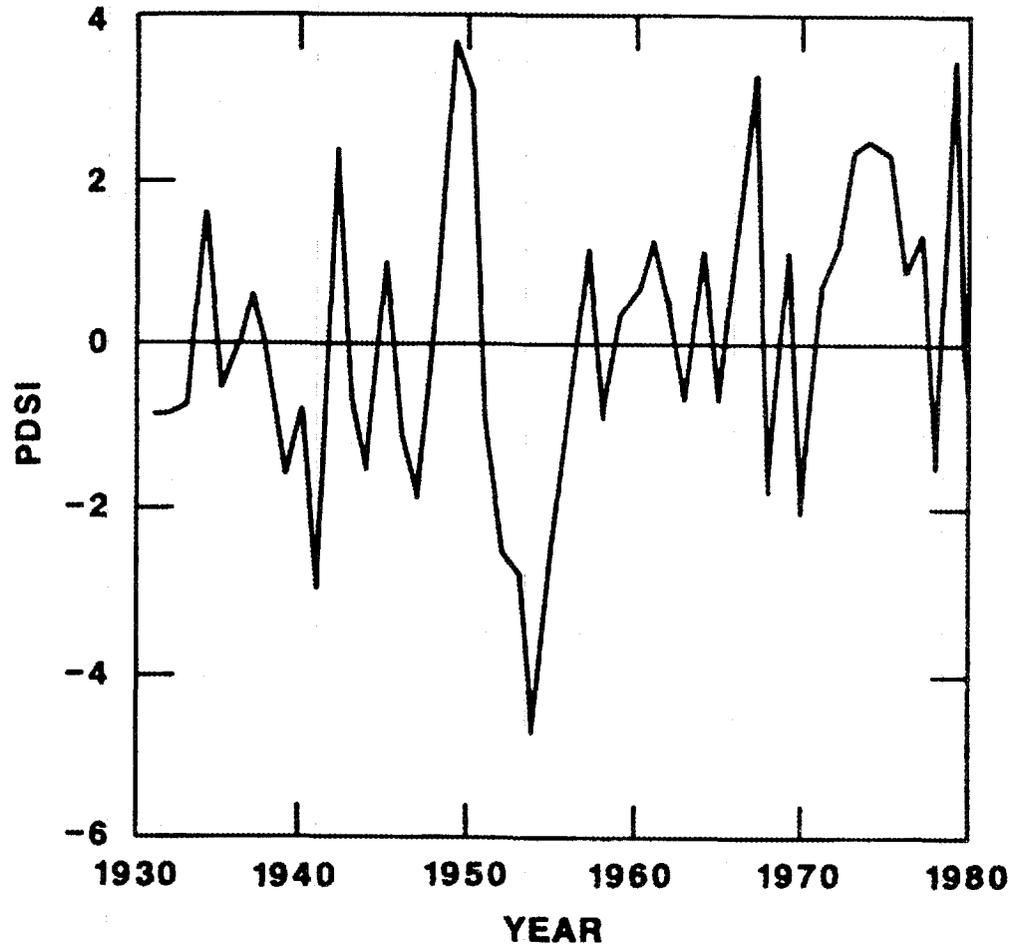
**SEPTEMBER PDSI, EAST TENNESSEE
AND WESTERN NORTH CAROLINA**

Fig. 3. September Palmer Drought Severity Index (PDSI) values for regional weather data from East Tennessee and western North Carolina.

data from the growing season. Growth of red spruce was found to correlate best with PDSIs from September of the year prior to growth, indicating the effect of summer drought on stored food reserves for the following year.

The PDSI for eastern Tennessee and western North Carolina, which we have derived from monthly precipitation totals and temperature means for the Knoxville weather station (ID No. 13891) of the National Oceanic and Atmospheric Administration climatic data base (National Climatic Center, Asheville, North Carolina), clearly shows the severe drought of the 1952-1954 interval (Fig. 3). It is interesting that the extent of drought-induced growth suppression was somewhat more severe at low elevations. Since the input data from which the PDSI was derived were also from low elevations, it is possible that the drought was most severe at these lower elevations. The additional precipitation derived from cloud deposition at higher elevations may have been a factor in reducing the impact of the drought at these sites. At Camels Hump, Vermont, precipitation amounts increased with elevation when total precipitation increased by a factor of about 50% over a 600-m elevation range (Siccama 1974).

The generally high availability of moisture during the last 20 years, including the second period of growth decline noted in Figs. 1 and 2, is readily apparent in Fig. 3. It is apparent from these data that the growth decline initiated in the mid 1960s did not occur in response to drought as characterized by this monthly index. Growth declines in the early 1960s at nearby Mt. Mitchell, North Carolina, also apparently occurred in the absence of shorter-term drought based on weekly weather records at that site (Bob Bruck, personal communication).

Growth decline during the interval 1972-1981 at each elevation and aspect is summarized in Table 1. Two reference intervals were used for this comparison: a 30-year interval (1932-1961) immediately preceding the decade within which the decline began and the last 10 years of that interval (1952-1961), a period when the previously discussed drought (see Fig. 3) caused obvious growth depression across all sites. The latter interval provided a conservative basis for evaluating the

severity of the more recent growth trends that were a focal point of this study in relation to a known natural stress.

Growth-trend data summarized in Table 1 reflect the increasing severity of the observed growth decline with increasing elevation. At high-elevation sites on both aspects, radial growth was <50% of what occurred during the 1932-1961 reference interval and <40% of what occurred during the decade of the 1950s when the drought occurred. During the most recent decade, mean radial increment at the two lowest elevation sites averaged 97% of the annual increases in the 1932-1961 interval. Percentage of growth change using the 1952-1961 reference period for pooled data from both upper sites ($n = 30$) was -42.9%. Application of a Kruskal-Wallis test on percentage of growth change for 1972-1981 using the 1952-1961 reference period showed that, on both aspects, trees from the highest elevation declined more significantly ($P < 0.05$) than those at the two lowest elevations (i.e., the percentage of growth change at 1845 m on both aspects was significantly larger than percentage of growth changes at both 1385 m and 1540 m). No other comparisons differed at statistically detectable levels (Table 2).

The timing and extent of the 1960s growth decline was analyzed by determining both the percentage of cores at each site that exhibited the abrupt transition to narrow rings (Table 1) previously reported by Johnson and Siccama (1983a) for northern sites and by examining the number of cores from each elevation that initiated an abrupt growth reduction without subsequent recovery during each year (Fig. 4). Table 1 indicates that the growth decline at the highest two elevations, 1720 m and 1850 m, affected a larger fraction of trees. A maximum of nearly 66% of the total cores showed sustained decline at the southwestern site. By contrast, no cores showed abrupt decline at the 1540-m site on the northeastern slope. Of the 120 cores in the Mt. LeConte sample, approximately 33% showed this abrupt decline without subsequent recovery.

The data on basal area of stands as well as the data on tree age shown in Table 1 provided an opportunity to test two hypotheses for the recent growth decline: stand competition and tree senescence. Interest

Table 2. Results of Kruskal-Wallis tests (j values) when comparing percentage of growth change (1972-1981) to the reference period (1952-1961) for three elevations and two aspects on Mt. LeConte

Elevation	<u>Northeast slope elevation (m)</u>			<u>Southwest slope elevation (m)</u>		
	1540	1720	1845	1540	1720	1845
1385	1.03	0.31	3.88 ^a	0.07	1.70	6.72 ^b
1540		2.04	9.16 ^b		2.22	8.31 ^b
1720			1.81			2.29

^aP = 0.05

^bP = <0.001

Kruskal-Wallis tests of differences in rotative radial growth rate (1972-1981 compared to the 1952-1961 reference period) for 15 trees (30 cores). Sampled at each of 3 elevations and 2 aspects on Mt. LeConte. J values for each comparison between elevations in the matrix are shown.

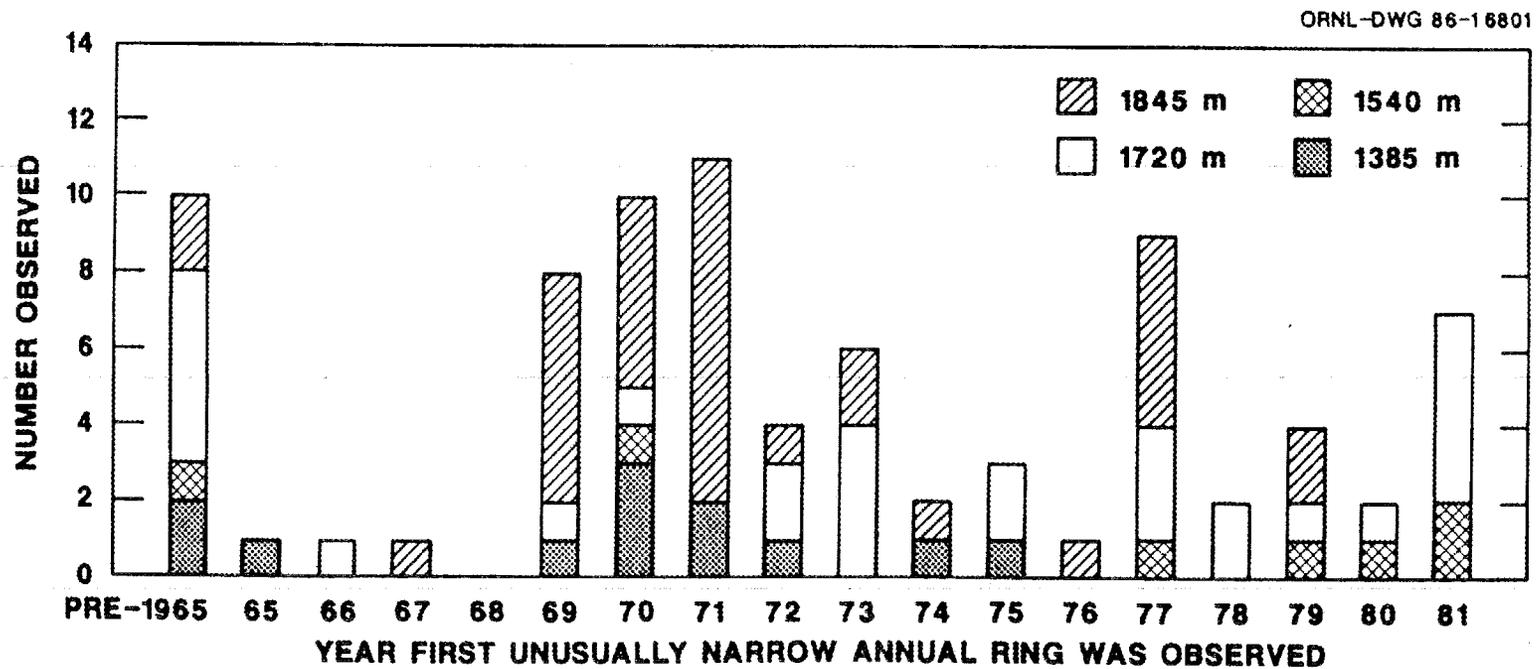


Fig. 4. Frequency histogram of the number of cores in which a sustained shift to unusually narrow rings was observed for red spruce from four elevations on Mt. LeConte. Data from southwestern and northeastern slopes have been combined.

in stand competition as a triggering stress has been stimulated by recent analysis by Zedaker et al. (1987) of historical stand growth tables published by Meyer (1929). The Zedaker article focused on growth-trend data from pure fully stocked red spruce stands that developed as even-aged, second-growth forests on previously logged, burned, or pastured sites. These stands showed an abrupt slowing of growth at about 50 years after reaching breast height (1.4 m). This response was most pronounced on poor-quality sites. The stocking level at which this slowdown occurred was approximately 35 m²/ha on poor-quality sites (site index 50) and 60 m²/ha on better-quality sites (site index 70).

In addition to the basal area of living and dead stems included in Table 1, Tables B-2 and B-3 contain data on stem density and species composition for the eight Mt. LeConte sites where cores were collected. On both aspects, red spruce was dominant at all but the lowest elevation sites, where hemlock dominated. Although estimates of basal area at the middle elevations on the northeastern slopes were small--reflecting low tree density with dense rhododendron undergrowth--diameters of cored individuals were comparable to those at other sites. Mean diameters of trees and distance to competitors were smallest at the highest elevation, indicating that the density of smaller trees is greater at higher elevation sites than at the lowest elevation sites (Appendix B).

Decreasing tree size with increasing elevation also was reported by Whittaker (1956) in the Smokies and by Foster and Reiners (1983) in the White Mountains of New Hampshire. The latter researchers also reported increased tree density with increasing elevation. Ninety-four percent of the basal area of dead stems at the higher elevations was due to mortality of Fraser fir presumably killed by balsam woolly aphid infestation; in fact, nearly half the total basal area at the two upper southwest sites was contributed by dead Fraser fir.

The stand responses observed on Mt. LeConte during the 1965-1981 period do not fit the model of a competition-induced slowdown on several counts. First, the stands themselves are unevenly aged, with a wide range of size classes and ages being represented, as is typical of natural gap-phase forests. In recent history there has been no known

event with a synchronizing disturbance to produce a cohort of even-aged trees which might reach maturity simultaneously. This is verifiable from the long-term growth record of existing trees. Furthermore, the pattern and severity of growth decline shows no consistent relationship to either stand stocking levels or average tree age. The growth of trees at the northeastern 1720-m site slowed by 33% at a total basal area of 12.7 m²/ha, while those at 49 m²/ha at 1540 m showed relatively little slowdown of growth over the 1971-1981 interval.

To determine if the effects of competition on changes in growth differed at higher and lower elevations, correlation coefficients were calculated for pooled data from both lower elevation stands and higher elevation stands; competition effects were small and not significantly different for stands at the different elevations ($r = -0.188$, $P = 0.2$ for the upper stands). Overall, correlations between growth decline and total competition (i.e., number of trees within the prism plot established around each tree) were very weak ($r = -0.193$, $P = 0.35$).

Observed growth decreases were also not correlated in any meaningful way with mean age of cored trees at each site as recorded in Table 1. Examination of the data on the degree of decline in that table shows that trees in both the 150-year and the 190-year age ranges can be found at both the highest and lowest elevations. In each case it is the high-elevation and not the low-elevation stand that shows the marked decrease in mean radial increment. Trees at the NE 1845-m site, for example, declined 2.5 times as much as those over 100 years older at the SW 1540-m site. Tree aging effects would not be anticipated at these ages since the growth of both the height and diameter of red spruce in natural unevenly aged stands is normally not affected by age. This is apparent from several articles reviewed by McLaughlin et al. (1987).

Subjective estimates of the vigor status of trees are summarized in Table 1. Vigor estimates were similar for all elevations on the southwest slope, but greater variation and more severe foliage loss was recorded on the northeast slope. Coincidentally, Baes and McLaughlin (1986) indicated higher levels of trace elements in tissues of trees from the eastern slopes of Mt. LeConte than from the western slopes. Least healthy trees were also observed at 1720 m on the northeast

slope. Because the trees at this particular site average more than 250 years old, senescence might be considered a contributing factor; however, trees of comparable age at 1540 m on the southwest slope appeared considerably healthier. The correlation between estimated vigor class and their percentage of growth change (based on growth during the 1972-1981 decade compared to growth during the 1952-1961 decade) was not significant ($r = -0.105$, $P = 0.252$).

This supports the contention by Bruck (1984) that physical appearance of individual trees has little relationship to their present growth pattern. Mean values of the mortality of spruce on the southwest slope (8.7%) and at lower elevation (8.2%) were nearly twice that observed on the northeast slope or at higher elevations, respectively. However, overall mortality of red spruce at these sites was quite low compared to values reported for declining red spruce stands at high-elevation stands in the Northeast (Johnson and Siccama 1983a).

DEAD RED SPRUCE SURVEY

Dead red spruce trees were sparse in all areas studied (comprising less than 5% of all red spruce tallied). This observation is supported by results of a more systematic survey of fixed plots in the Smokies as reported by C. Eagar (National Park Service unpublished data). The relatively low mortality levels observed in this study, coupled with the fact that it was very difficult to determine the date of death of trees by cross-dating, led to reduced emphasis on efforts in this area.

Composition of sites at which dead red spruce cores were obtained is shown in Table B-4. Red spruce was clearly dominant, with Fraser fir and yellow birch the only other canopy species present. Diameters of competitors were smaller than those of the dead trees. Most cored trees were large and older (mean number of rings at breast height = 181). Mortality figures for red spruce at the ten sites at which trees were cored were necessarily inflated because the dead cored trees were included in the tally. As already indicated, only 5% of all red spruce tallied in all study areas were dead. Figure 5 shows the general trend of growth during the last 50 years before the death of these trees.

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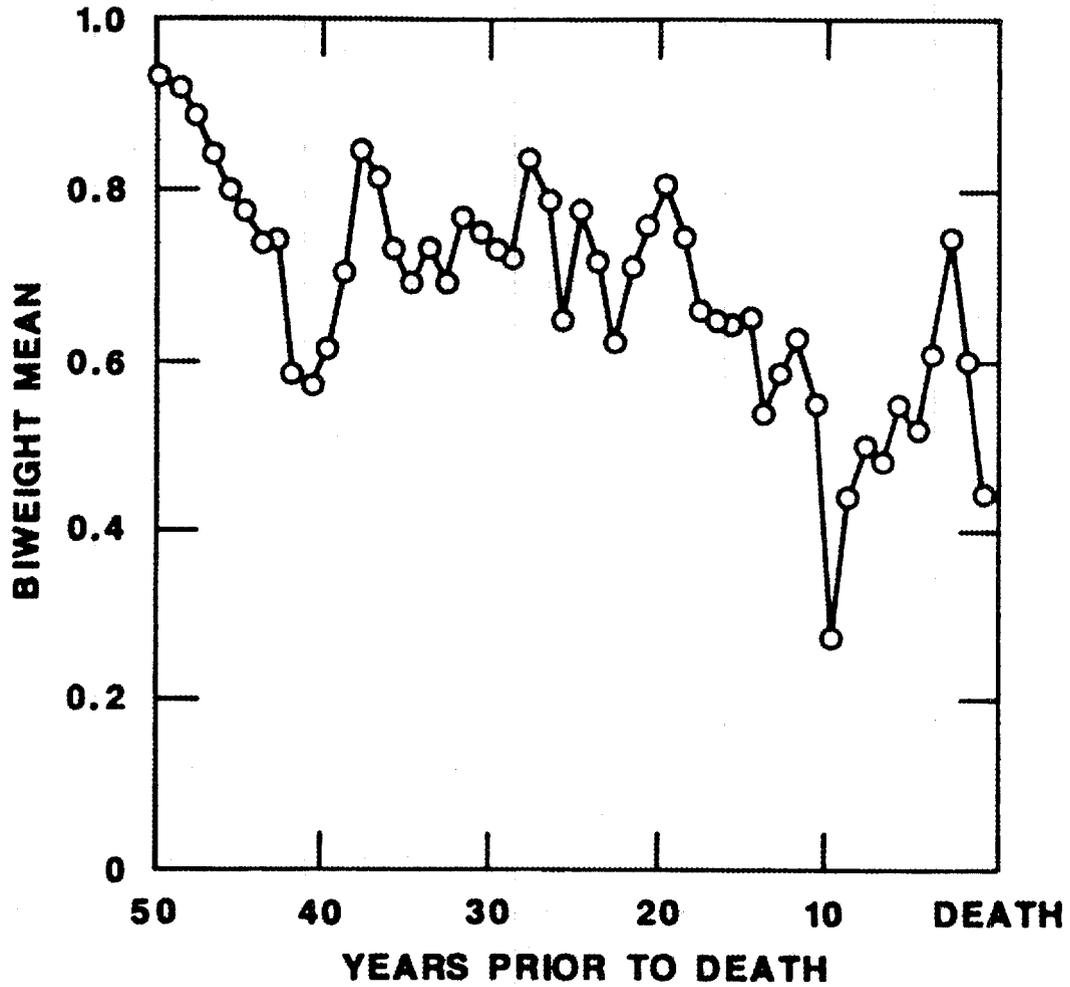
SMOKIES DEAD SPRUCE

Fig. 5. Biweight mean values of annual radial increment data for 20 red spruce cores collected from 10 dead red spruce trees (2 cores per tree) in the Mt. Collins area.

There seems to be no definite sudden onset of decline, but rather a general slowing of growth throughout the entire period. Mean annual increment was less than 1 mm for each of the last 50 years and had decreased to <0.5 mm at time of death. The single unusually low value 10 years prior to death of these trees is apparently due to chance coincidence of narrow rings in all cores, since that particular ring was not necessarily produced in the same year by all trees. Further, the exact year of death is uncertain because these cores have not been crossdated rigorously. By comparison, annual radial increments of living red spruce at Mt. LeConte and Mt. Sterling (discussed in the next section) exceeded 1 mm except during the last two decades at sites where severe decline occurred. Annual growth increments of ≤ 0.5 mm were noted during this time at the upper two elevations on the northeast slope and at the highest elevation on the southwest slope of Mt. LeConte, where growth rates of 0.3 to 0.4 mm per year were observed (see Figs. 1 and 2).

MT. STERLING SIZE/AGE CLASS SURVEY

Summary data on site characteristics, stand basal areas, vigor ratings of cored trees, and growth decline characteristics based on samples collected from three size classes of red spruce sampled at Mt. Sterling are recorded in Table 3. Growth and vigor ratings based on the separation of five age classes are shown in Table 4. Data on species composition and on size and spacing of trees competing with cored trees at this site are included in Table B-5.

The understory at this site had a relatively high density of fir seedlings and saplings, although fir was essentially absent from the overstory, presumably due to destruction by the balsam woolly aphid. Basal area of live trees was composed mainly of spruce, whereas basal area of dead trees was primarily attributable to fir (Appendix B). Vigor status for the middle size class (25-40 cm dbh) was lowest, while small individuals showed no obvious foliage loss. The generally unhealthy appearance of the middle-sized spruce may be indicative of their competition with Fraser fir before its demise, since it is this

Table 3. Summary data for Mt. Sterling, Great Smoky Mountains National Park (all measurements taken at elevation 1770 m^a)

	Size class, cm (dbh)		
	10-25	25-40	>40
Site-specific aspect (deg) ^b	102	102	102
Inclination (°) ^b	41	41	41
Total basal area (m ² /ha) ^c		32.5	30.4
Live basal area (m ² /ha) ^c		27.5	23.3
Dead basal area (m ² /ha) ^c		5.0	7.1
Mean age (±S.E.) ^d	73 (9.3)	78 (3.7)	127 (12.5)
Mean dbh of cored trees (cm) (±S.E.)	16.7 (1.33)	31.8 (1.20)	49.2 (1.57)
Percentage of individuals in vigor class ^e :			
0	100.0	26.7	80.0
1	0	66.7	20.0
2	0	6.7	0
3	0	0	0
4	0	0	0
Percentage of cores showing decline without recovery ^f	30.0	50.0	56.7
Percentage of growth change (1972-1981 compared to 1952-1961) ^g	+1.5	-38.0	-36.2

^aApproximate, based on locations of sample sites on 7.5 min U.S. Geological Survey topographic maps.

^bMean pf values recorded at each cored tree ($\bar{n} = 45$).

^cMean of prism (2.5 metric) plots around each cored tree (not done for smallest sized class, $\bar{n} = 5$ for middle size class, $\bar{n} = 15$ for largest size class).

^dBased on mean number of annual rings counted to pith or innermost annual ring observed for each cored tree ($\bar{n} = 15$ per size class); this does not consider possible missed annual rings due to not hitting exact center or growth occurring prior to attaining coring height.

^eSubjective evaluation of foliage loss of cored red spruce trees only, using a rating scale described in the text.

^fBased on inspection of individual cores for date of abrupt transition to unusually narrow growth increments ($\bar{n} = 3$ per size class).

^gBased on mean growth of cores during reference period 1952-1961 and mean growth of these same cores during 1972-1981 ($\bar{n} = 30$ per size class).

Table 4. Characteristics of different age classes of trees on Mt. Sterling

	Tree age (years)				
	<65 (n = 10)	65-84 (n = 13)	85-104 (n = 9)	105-124 (n = 6)	>124 (n = 7)
Mean age (\pm S.E.) ^a	47 (3.1)	75 (1.2)	95 (2.6)	111 (2.4)	172 (13.3)
Percent age of individual trees showing growth trend decline ^b	20	62	56	67	100
Mean growth (mm) (\pm S.E.) 1952-1961	1.250 (0.1872)	1.774 (0.1911)	1.537 (0.1456)	2.064 (0.2512)	1.585 (0.1916)
Mean growth (mm) (\pm S.E.) 1972-1981	1.582 (0.2266)	1.236 (0.2031)	0.952 (0.1795)	1.181 (0.1773)	0.847 (0.1526)
Percentage of growth change (1972-81 compared to 1952-61) (\pm S.E.E)	+52.8 (29.22)	-29.3 (9.19)	-33.8 (12.81)	-40.0 (10.82)	-41.7 (12.00)
Mean dbh (mm) (\pm S.E.)	169 (25.0)	334 (21.9)	314 (46.9)	380 (41.3)	504 (45.1)

^aAges based on mean number of annual rings counted to pith or innermost annual ring observed for each cored tree; this does not consider possible missed annual rings due to not hitting exact center or growth occurring prior to attaining coring height.

^bBased on inspection of individual cores for presence of abrupt transition to unusually narrow growth increments; if one of the two cores for each tree exhibited this pattern, the tree was considered to exhibit growth trend decline.

size class with which the fir were most competitive (C. Eagar, personal communication). All of the individuals within the largest size class were classified as healthy.

Biweight means (Fig. 6) for cores collected at this site show an obvious decline in the largest trees and slight decline in the middle-sized trees, beginning in the 1960s. These trees had apparently recovered from the drought of the 1950s before beginning the more recent decline during a relatively wet period, further weakening the hypothesis of drought as a primary causative factor. These data also show a shift toward improved growth since 1980, as was observed on the southwest slope of Mt. LeConte. A similar decline in the smallest trees, commencing in the 1960s, is followed by an increased growth since the mid-1970s.

The observed increase in the growth of the small trees during the 1930s is the result of the interim addition of several young cores (i.e., those exhibiting vigorous growth) to the mean series of the small trees. The more recent "release" is probably due to the death of surrounding Fraser fir and is not evident in data for the larger trees, which presumably were effective canopy and midcanopy competitors prior to the death of these Fraser firs. The release of these small trees supports Saunders' report (1978) that the growth of spruce (diameter and height) responded favorably to decreased midcanopy and canopy density because of the death of aphid-infested trees.

Effects of the drought of the 1950s are shown in the data for the larger trees. The mid-1950s depression was followed by a period of growth restoration before appearance of the recent growth-trend decline. There is evidence of drought effects on the growth of the smallest trees during this period also, but there seems to be little recovery before onset of the growth-trend decline of the 1960s. This apparently reflects an inability of these smaller and generally younger suppressed trees to recuperate from the stress of drought as readily as the larger and older trees at this site. On the other hand, these same trees responded well to release from suppression. It appears that the stress responsible for the recent growth-trend decline was overcome by release in these subcanopy trees. Continuation of the more recent

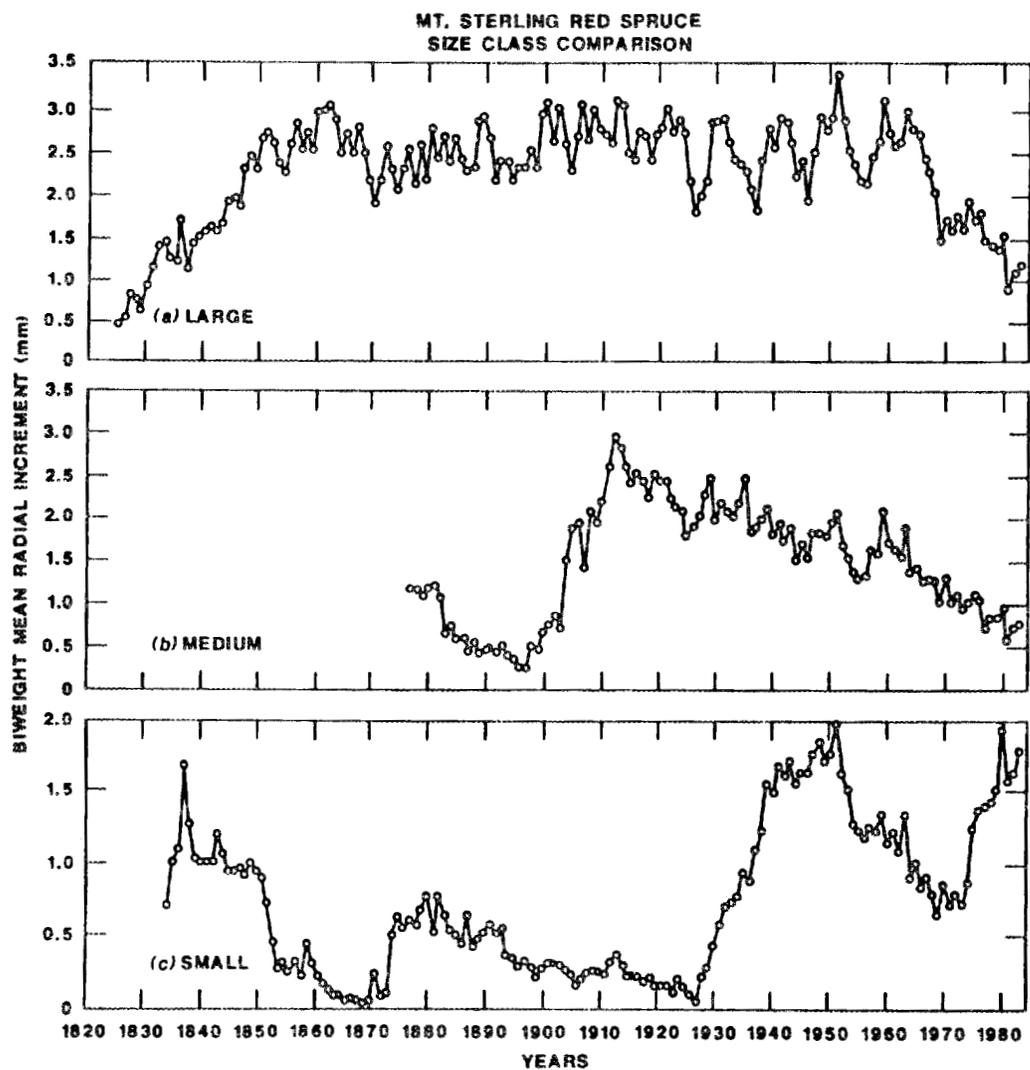


Fig. 6. Biweight mean plots of annual radial growth of 30 increment cores collected from 15 red spruce tree (2 per tree) in each of 3 diameter-size classes from Mt. Sterling.

decline in the larger trees, however, suggests that the present stress on their growth is more severe or more prolonged than drought, since they recuperated from drought but have not yet recovered from this more recent decline.

Forty-six percent of all cores showed abrupt transition to unusually narrow annual growth increments since 1950. The frequency of cores showing this pattern was higher for the larger size classes (>50%) than for the smallest size class (30%) (Table 3). Figure 7 demonstrates that the plurality of trees initiated the unusually narrow ring pattern in 1977. This is similar to the Mt. LeConte data, follows the local 1976 drought noted by Eagar (NPS, personal communication), and coincides with the high growing season concentrations of ozone reported for 1977 (McLaughlin et al. 1982). In general, the largest trees showed earlier onset of this pattern than did the other size classes; the middle-sized trees exhibit more recent onset.

Since several of the cored trees did not have annual rings as early as the 1930s, the decade of 1952-1961 was used as a reference period with which to compare growth during the 1972-1981 decade. Growth in the middle-sized and largest trees decreased by approximately 37% in the recent decade, whereas that of the smallest trees increased slightly (Table 3). Wilcoxon signed-rank tests for detection of statistically different growth rates between the two periods yielded no significant difference ($P > 0.05$) for the small trees, but differences ($P < 0.01$) for medium-sized and large trees were significant ($P < 0.01$). Since the reference period coincides with drought in the area (Fig. 3) and the decrease in growth during the relatively wetter 1970s is still evident as with the Mt. LeConte data, the hypothesis of drought as a major contributing factor of decline is not supported.

Since data collected from Mt. Sterling could be stratified by age classes (based on the date of pith or the innermost ring), we examined the possible existence of a relationship between degree of growth decline and age of cored trees at that site (Table 4). The abrupt transition to very narrow rings was found in at least one core of all trees over 124 years old, but occurred in only 20% of the trees less than 65 years old. While growth of the youngest trees was greater in

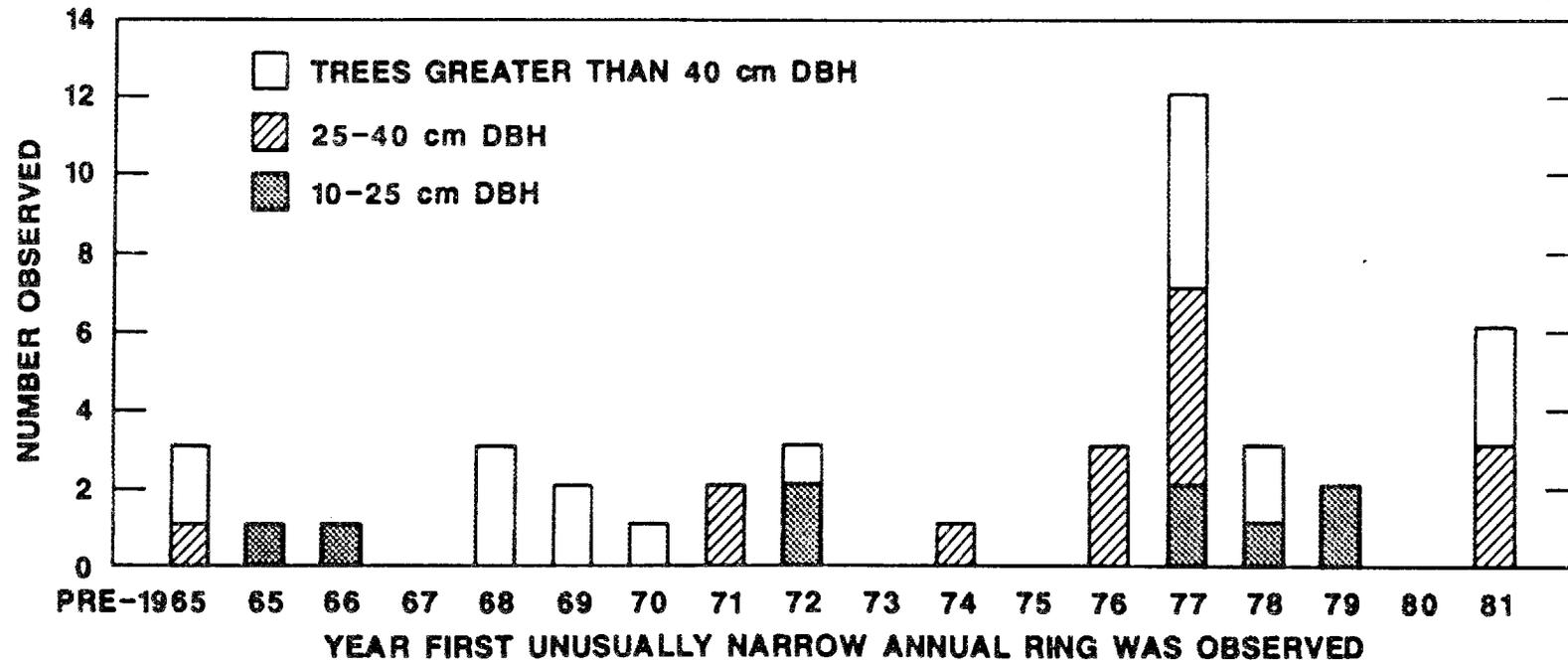


Fig. 7. Frequency histogram of the number of cores in which a sustained shift to unusually narrow rings was observed for cores from 15 red spruce trees in each of 3 diameter-size classes on Mt. Sterling. (Two trees did not have any unusually narrow rings.)

the 1972-1981 decade than in the 1952-1961 decade, the opposite was true for the older trees. The Pearson product-moment correlation coefficient between age and percentage of growth change was -0.422 ($P = 0.004$), demonstrating a strong statistical relationship between growth change and tree age at this site. However, this apparent divergence from the results of the Mt. LeConte survey, where a lack of an age-growth relationship was noted, must be qualified by the realization that on Mt. Sterling, age, size, and competitive status were strongly interactive variables (see Table 3). Thus this apparent age-growth relationship at Mt. Sterling is more likely attributable to the fact that the younger, more recently released trees less than 65 years old (see Table 4) underwent an additional change in competitive status as Fraser fir mortality increased.

The Kruskal-Wallis statistic, based on a comparison of the growth during the 1972-1981 decade between younger and older trees, indicated that the younger trees grew significantly faster ($P < 0.05$) than did the older trees during this interval. The same statistic calculated for the percentage growth change between the two decades in these two groups produced similar results [i.e., a $+6.39\%$ growth change for younger trees was significantly greater ($P < 0.05$) than the -38.05% growth change recorded for the other trees]. However, any comparisons of age or diameter relationships at this site will be strongly confounded by the competitive shift apparent in the recent growth release that occurred in the smaller younger trees (see Fig. 6).

NORWAY SPRUCE SURVEY

The two sites at which Norway spruce was sampled (1485- and 1350-m elevations) were composed predominantly of Norway spruce, although the lower site had a considerable mixture of hardwoods, especially sugar maple and silverbell (Table B-6). Biweight means and indices (Fig. 8) of the 15 tree samples at each site demonstrated a shorter period of growth response to the drought of the 1950s and a more rapid recovery than was observed for red spruce. The rapid recovery following drought is probably attributable to the more vigorous growth associated with the younger age of the Norway spruce. A growth decline did occur at both

NORWAY SPRUCE

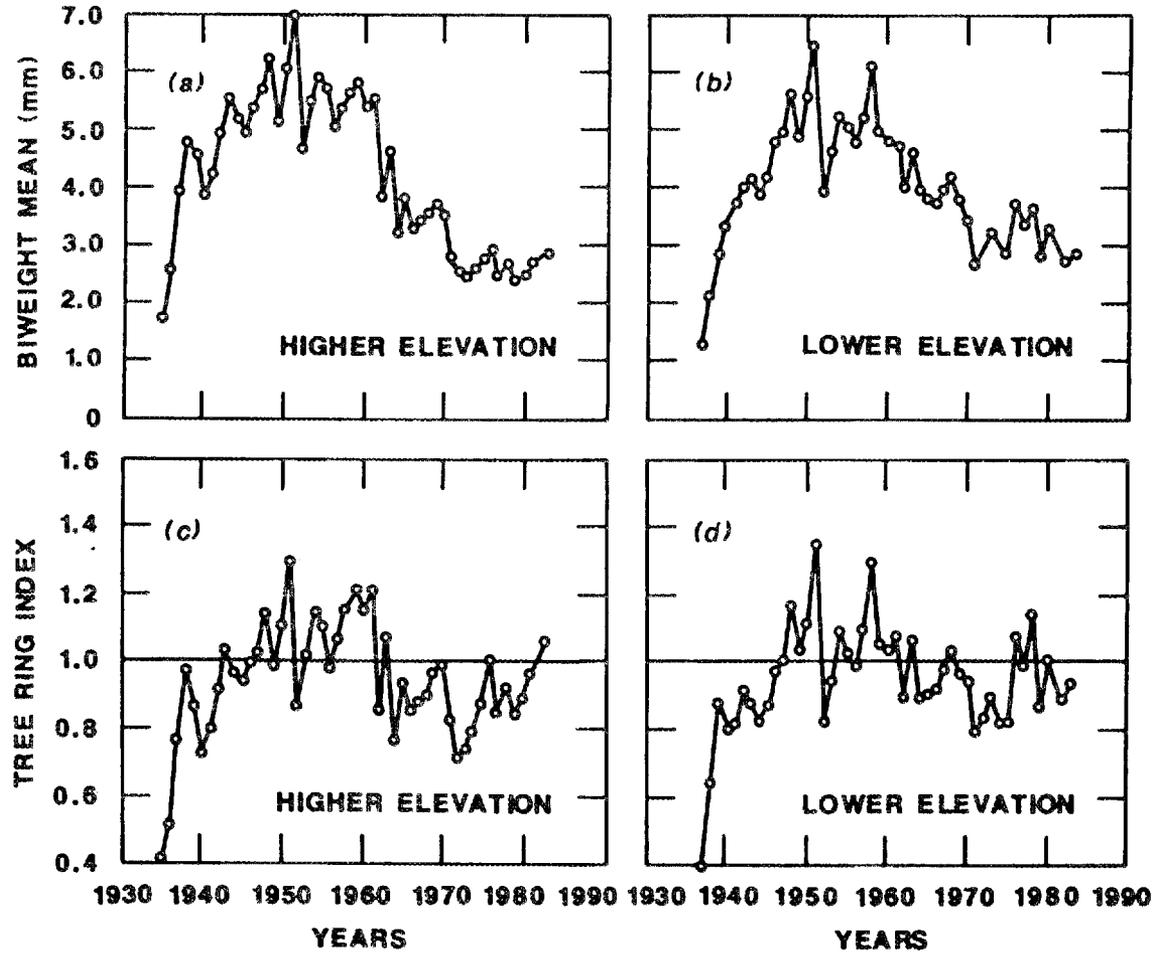


Fig. 8. Biweight mean and tree-ring indices of annual radial growth of 30 Norway spruce increment cores collected from 15 trees (2 per tree) from each of 2 elevations on the east slope near Grassy Branch trail.

elevations commencing in the early 1960s, and the decline at the higher elevation appears somewhat more pronounced. By comparison, this is somewhat earlier than the decline of red spruce observed on Mt. LeConte (Figs. 1, 2) or Mt. Sterling (Fig. 6). Also, decline of these Norway spruce was evident at a lower elevation than the decline observed for red spruce.

Summary data on site characteristics, stand stocking, vigor ratings, and growth patterns are included in Table 4. There was little mortality at these sites, although vigor status of Norway spruce was considerably less (<60% estimated to be unhealthy) than recorded for red spruce (see Table 1). There was also little difference in vigor status between the two elevations. Growth for the period 1972-1981 was compared with the reference period of 1952-1961 because of the young status of all trees. Trees at both elevations showed decreases in growth during the past 20 years, and the decrease at the higher elevation was somewhat more pronounced (52% vs 35% for the lower site).

The relatively young and uniform age of these Norway spruce stands suggests the possibility that stand and competition effects may have contributed to the growth declines observed under these conditions. Possible effects of canopy closure as a contributing factor in the decline of these Norway spruce cannot be discounted, although this seems less likely at the lower elevation where the trees were more widely spaced. Basal areas of these two sites (22.6 m²/ha lower and 31 m²/ha upper; see Table 5) were approximately 50% below basal areas of good-quality (site index 50) red spruce stands at which strong growth reduction due to competitive pressure occurs (Meyer 1929). Whereas annual increment size of red spruce (i.e., at Mt. LeConte and Mt. Sterling) declined from values of around 1.5 mm to around 0.5 mm, increment size in Norway spruce decreased from around 5.5 mm to around 3 mm, presumably reflecting differences in ages, stand structure, and genetic-based growth potentials of specimens. In any case, existence of a decline in these young planted trees demonstrates the pervasiveness of whatever stress or combination of stresses is contributing to growth-trend declines in spruce in the Smokies.

Table 5. Comparison of variable for two Norway spruce sites in Great Smoky Mountains National Park

	Elevation (m) ^a	
	1325	1485
Site-specific aspect (deg) ^b	204	130
Inclination(%) ^b	56	60
Total basal area (m ² /ha) _ε	22.6	31.1
Live basal area (m ² /ha) _ε	21.4	30.2
Dead basal area (m ² /ha) _ε	1.2	0.9
Mean dbh of cored trees (cm) ±S.E.	41.2 (1.70)	40.4 (1.86)
Mean age ^d	38	41
Percentage of individuals in each vigor class ^e :		
0	20.0	26.7
1	66.7	60.0
2	13.3	13.3
3	0	0
4	0	0
Percentage of growth change (1952-1961 compared to 1972-1981) ^f	-35.6	-52.0

^aApproximate, based on locations of sample sites on 7.5 min U.S. Geological Survey topographic maps.

^bMean of values recorded at each cored tree ($n = 15$ per site).

^cMean of prism (2.5 metric) plots around every other cored tree ($n = 8$ per site).

^dBased on mean number of annual rings counted to pith or innermost annual ring observed for each cored tree ($n = 15$ per site); this does not consider possible missed annual rings due to not hitting exact center or growth occurring prior to attaining coring height.

^eSubjective evaluation of foliage loss of all Norway spruce trees within prism plots using a rating scale described in the text.

^fBased on mean growth of cores during reference period 1952-1961 and during 1972-1981 ($\bar{n} = 28-30$ cores per site).

SUMMARY AND CONCLUSIONS

The principal findings of this survey of spruce growth trends in the GSMNP may be summarized as follows:

1. Growth-trend declines in red spruce are evident at all higher elevations sampled in this study, the severity of decline increasing with elevation on Mt. LeConte.
2. Growth-trend declines on Mt. LeConte exhibited a greater relationship to elevation than to either tree age or substrate.
3. A growth-trend decline during a drought period occurring in the 1950s is evident in biweight means at all sites and was followed by recovery of growth; the more recent decline that followed at most sites, however, does not coincide with drought.
4. The last 50 years of growth of recently dead red spruce trees exhibited only a gradual slowing trend throughout the period. This rate of growth (<1.0 mm annually) is comparable to the rate observed in sites of severe decline (e.g., highest elevations on Mt. LeConte).
5. On Mt. Sterling, abrupt transition to unusually narrow growth increments was exhibited more frequently by older trees than by younger ones. The fact that the younger and smaller trees have recovered from the decline pattern suggests that positive release effects have occurred in association with the high mortality of competing Fraser fir.
6. The pattern of decline observed in Norway spruce suggests that this species is more sensitive than red spruce to whatever stress or combination of stresses is contributing to decline in both of these species.

These results support the more general conclusions of later studies of red spruce in the Great Smoky Mountains, compiled by Van Deusen (1988). The summary of that document states that mortality rate and radial growth of high-elevation red spruce/Fraser fir forests of the southern Appalachians have experienced change since approximately 1960, and that scientific interest in a study of these forests has increased because atmospheric pollution is a possible cause of the change. It

was also noted, however, that the actual causes of the observed changes are as yet uncertain. There is one conclusion by Van Deusen (1988) to the effect that the sensitivity of the stand to climate appears to be increasing. Our analysis suggests that while drought may explain an earlier decline, it cannot explain the most recent decline (our conclusion 3, above). This appears contradictory to the conclusion in Van Deusen (1988). This may be because Van Deusen's definition of climate was arbitrary (e.g., based on the calendar year rather than on the growing season), or because our analysis was limited to drought, or both. However, there may be another explanation, and we suggest the following as meriting further investigation. Sensitivity to drought may diminish when drought diminishes, but sensitivity to some other climatic variable (or variables) may then increase, especially if some other stress (e.g., insects or environmental deterioration) is also present. We note that the results of Cook, presented in Van Deusen (1988), suggest that the possibility of increased sensitivity to summer temperature might be a promising hypothesis to investigate along this line.

Cook (1988) also noted differences between the situation for southern red spruce and the situation for northern red spruce. Some differences were also apparent in the work of McLaughlin et al. (1987), and these should be kept in mind when interpreting the results of studies on only southern (or northern) trees.

This exploratory study of growth trends of red and Norway spruce in the Great Smoky Mountains National Park was initiated to provide additional data on red spruce growth responses for comparison with previously collected elevational response data for red spruce in the Northeast obtained by Johnson and Siccama (1983a). The data from Mt. LeConte and Mt. Sterling represent the only elevational data on red spruce radial growth responses included (with the Johnson and Siccama data) in a larger data base (McLaughlin et al. 1988). Because of the high visibility of the reported decline of red spruce in the eastern United States, the red spruce data set, one of the largest in the McLaughlin et al. (1988) data base, has recently been examined using a variety of newly developed time-series techniques (McLaughlin et al.

1987). Those analyses were designed to examine the strength and spatial and temporal consistency of the observed growth decline in relationship to historical precedents in the tree-ring record and to determine the influences of climate and competition on observed growth responses.

The conclusions of that study were that the recent radial growth decreases of red spruce were the strongest observed over the past 200 years of record of surviving trees, and the pattern of growth decrease would not be predicted based on the relationship between red spruce growth and either climate (principally temperature) or stand competition. The eight Mt. LeConte sites were a part of these analyses, which demonstrated that the decline of red spruce in southern stands was, unlike the northern situation, confined principally to high elevations, somewhat weaker overall, and delayed by 5 to 10 years (compared to an initiation date in the late 1950s and early 1960s in the North). Time-series analyses of responses of radial growth to temperature over the past 80 years using the techniques of Cook (1987) showed that spruce on both aspects of the high-elevation sites on Mt. LeConte grew more slowly than predicted by past growth-climate relations primarily during the late 1960s and early to mid 1970s. This period is the one that in this study shows the highest frequency of sustained shifts to the pattern of very narrow rings.

Thus the responses that we have examined in this report appear to be a part of a larger regional decline of red spruce in the Appalachians of the eastern United States. An additional, more broadly based and systematic growth-trend survey conducted by the Tennessee Valley Authority in the mountains of Tennessee and North Carolina has likewise confirmed the existence of an anomalous decline at high elevations across the region (Van Deusen 1988).

The causes of the observed radial growth decline of red spruce in the Appalachians are still not well understood (McLaughlin 1985); however, increases in emissions of atmospheric pollutants from combustion of fossil fuels across the region during this same time period must be considered a possibility. During the next few years, the mechanistic studies that are currently proceeding across the region and specifically in the Great Smoky Mountains National Park as a part of the

U.S. Forest Service/EPA Forest Response Spruce Fir Research Program and the Electric Power Research Institute-sponsored Integrated Forest Studies should make major headway in exploring both anthropogenic and natural causes for the observed responses (Anderson et al. in press; Lindberg et al. 1988; McLaughlin et al. in press).

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Appendix A

GENERAL DESCRIPTION OF THE FORESTS IN THE GREAT
SMOKY MOUNTAINS NATIONAL PARK

The Great Smoky Mountains National Park extends along the general southwest-northeast border between Tennessee and North Carolina at approximately 83°28'W longitude and 35°39'N latitude. The varied topography provides for an outstanding diversity of life; there are excellent stands of old-growth forests, and several species attain their world-record size in the park. The vegetation, climate, and topography of the Smokies has been described in several studies (Braun 1964; Whittaker 1956; Shanks 1954; Crandall 1958; King and Stupka 1950; King et al. 1968).

Among the various types of vegetation found in the Smokies, the unique subalpine red spruce [*Picea rubens* (Sarg.)]-Fraser fir [*Abies fraseri* (Pursh) Poiret] forest occupying the high-elevation peaks, mainly in the eastern portion of the park, is the most extensive and best developed in the southern Appalachians. This community in the Smokies has been extensively studied (Cain 1935, Oosting and Billings 1951, Whittaker 1956, Crandall 1958). Red spruce is the most characteristic species of both the northern and southern high-elevation forests. Fraser fir, characteristic of the southern high-elevation forests, reaches its northernmost limit on Mt. Rogers in Virginia.

Whittaker (1956) recognized three forest types along the elevational gradient within the spruce-fir zone in the Smokies: spruce-dominated forest (1372 to 1646 m), spruce-fir forest (1676 to 1859 m), and fir-dominated forest (above 1859 m). On the average, the density of fir stems begins to exceed that of spruce at around 1707 m, although canopy dominance does not change until around 1829 m because of the generally larger size of spruce. At any elevation, fir increases toward more mesic sites. At elevations below 1372 m, cove hardwoods (e.g., *Aesculus octandra* Marshall, *Fagus grandifolia* Ehrhart, *Halesia carolina* L.) form an admixture with spruce and hemlock [*Tsuga canadensis* (L.) Carr.]; moving up the elevational gradient, these hardwood species and hemlocks are replaced by *Betula lutea* Michaux f., *Acer spicatum* Lam., *Acer pennsylvanicum* L., and *Amelanchier arborea* (Michaux f.) (Fernald 1950). At the highest elevations in fir-dominated forests, *Sourbus americana* Marshall may be the only hardwood species present.

In contrast to the paucity of overstory species at the high elevations, the understory is relatively diverse, its composition changing primarily along the presumed moisture gradient rather than with elevation (Whittaker 1956). Characteristic shrubs are *Viburnum alnifolium* Marshall, *Rhododendron catawbiense* Michaux, and *Vaccinium erythrocarpum* Michaux.

Unfortunately, the spruce-fir forest of the Great Smoky Mountains National Park has not remained free from disturbance. The balsam woolly aphid (*Adelges picea* Ratzenburg) attacks Fraser fir and was first detected in the Smokies in 1963 (Amman and Speers 1965). Currently only a few stands of Fraser fir in the park remain healthy, and even they are infested (Eagar 1984). The effect of the aphid on the composition of the spruce-fir forest is exemplified by data recorded in 1983 from a site at approximately 1676 m on the northwest slope of Mt. LeConte. Sixty-one dead fir stems were counted among a total of 187 stems (2.5 cm dbh and greater) in a 0.1-ha quadrat (unpublished data, H. S. Adams and M. L. Lipford). These dead fir stems reduced the basal area at this site by 34 percent; the only live Fraser fir found were smaller than 2.5 cm dbh.

Appendix B

LOCATIONS, PHYSICAL DESCRIPTIONS, AND STAND CHARACTERISTICS
FOR SITES AT WHICH INCREMENT CORES WERE COLLECTED ON
MT. LECONTE, MT. STERLING, AND AT SURVEY SITES
FOR DEAD RED SPRUCE AND FOR NORWAY SPRUCE

Table B-1. Locations and physical descriptions of all sites at which trees were cored in this study

MT. LECONTE

- (A) Near Trillium Branch - 35°40'12"N lat, 83°25'52"W long.; 1372-1402 m elevation; 55-90° aspect; 40-70% inclination; approximately 1 km below junction of Trillium Gap and Brushy Mountain Trails and 20 m below and 60 m above Brushy Mountain Trail; overstory dominated by hemlock and red spruce with some yellow birch, silverbell, beech, red maple, and striped maple; dense rhododendron understory; Thunderhead sandstone substrate.
- (B) Trillium Gap Trail - 35°40'7"N lat, 83°25'58"W long.; 1524-1554 m elevation; 50-60° aspect; 40-65% inclination; approximately 12.5 km above junction of Trillium Gap and Brushy Mountain Trails and 0.5 km above Trillium Gap Trail on east side of the spur ridge; overstory consisted entirely of red spruce; dense rhododendron understory; Thunderhead sandstone substrate.
- (C) Trillium Gap Trail - 35°39'52"N lat, 83°25'52"W long.; 1707-1737 m elevation; 90-135° aspect; 60-70% inclination; approximately 3.5 km above junction of Trillium Gap and Brushy Mountain Trails and 30 m below Trillium Gap Trail; overstory dominated by red spruce with scattering of yellow birch and fire cherry; rhododendron understory; Thunderhead sandstone substrate.
- (D) Near Myrtle Point - 35°39'4"N lat, 83°25'36"W long.; 1829-1859 m elevation; 125-135° aspect; 75-85% inclination; approximately 2.0 km southeast of LeConte Lodge and 30 m below Boulevard Trail; overstory dominated by red spruce and Fraser fir with some scattered yellow birch and mountain ash; rhododendron understory; Anakeesta shale substrate.
- (E) West Point and Cliff Top - 35°49'4"N lat, 83°26'39"W long.; 1829-1890 m elevation; 190-210° aspect; 40-60% inclination; approximately 0.5 km above junction of Trillium Gap and Bullhead Trails on southwest slope of West Point and 0.5 km below Cliff Top and 25 m above Alum Cave Trail; overstory dominated by red spruce

Table B-1 (continued)

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- and Fraser fir with scattered yellow birch; rhododendron understory; Anakeesta shale substrate.
- (F) Alum Cave Trail - 35°38'57"N lat, 83°26'19"W long.; 1707-1737 m elevation; 225-230° aspect; 45-55% inclination; approximately 3.2 km above Alum Cave bluff and 50 m below Alum Cave Trail; overstory dominated by red spruce (and formerly Fraser fir) with scattered yellow birch and small Fraser fir; rhododendron understory; Anakeesta shale substrate.
- (G) Alum Cave Trail - 35°38'33"N lat, 83°26'36"W long.; 1524-1554 m elevation; 250-295° aspect; 35-55% inclination; approximately 1 km above Alum Cave Bluff and 50 m below Alum Cave Trail; overstory dominated by red spruce with some yellow birch; dense rhododendron understory; Anakeesta shale substrate.
- (H) Rainbow Falls - 35°39'37"N lat, 83°27'43"W long.; 1372-1402 m elevation; 190-350° aspect; 30-75% inclination; approximately 200 m above Rainbow Falls and 25 m above Rainbow Falls Trail; overstory dominated by hemlock and yellow birch with moderate amount of red spruce; also scattered buckeye, striped maple, red maple, red oak, serviceberry, and black cherry; dense rhododendron understory; Thunderhead sandstone substrate.

MT. STERLING

Location - 35°42'28"N lat, 83°7'12"W long.; 1765-1780 m elevation; 60-125° aspect; 20-50% inclination; approximately 0.5 km below the Mt. Sterling Fir tower and 20-50 m above and below Baster Creek Trail; overstory dominated by red spruce with scattered yellow birch and serviceberry; rhododendron understory; Thunderhead sandstone substrate.

INDIAN GAP

Location - (only dead red spruce) 35°36'38"N lat, 83°26'9"W long.; 1675-1685 m elevation; 190-200° aspect; 25-35% inclination; approximately 75-100 m above and to the right of the Indian Gap

Table B-1 (continued)

parking lot; canopy dominated by red spruce with widely scattered small living Fraser fir and numerous standing dead Fraser fir; scant undergrowth with some invasion of blackberry; Anakeesta shale substrate.

MT. COLLINS

Location - (only dead red spruce) 35°35'33"N lat, 83°28'14"W long.; 1775-1792 m elevation; 115-345° aspect; 2-20% inclination; approximately 0.4 km south of Mt. Collins shelter; canopy dominated by red spruce (formerly Fraser fir) with scattered live Fraser fir and yellow birch; scant understory of hobblebush and blackberry; Thunderhead sandstone substrate.

NORWAY SPRUCE

- (A) Lower Grassy Branch Trail - 36°37'15"N lat, 83°21'58"W long.; 1280-1341 m elevation; 20-235° aspect; 40-90% inclination; approximately 1.8 km above Kephart Prong shelter and 15-30 m above and below Grassy Branch Trail; canopy dominated by Norway spruce with silverbell, sugar maple, black birch, and beech the only other important components but with seven additional species encountered; Thunderhead sandstone substrate.
- (B) Upper Grassy Branch Trail - 35°37'37"N lat, 83°21'38"W long.; 1475-1490 m elevation; 125-135° aspect; 55-65% inclination; approximately 3.4 km above Kephart Prong shelter and 25-30 m below Grassy Branch Trail; canopy dominated by Norway spruce with scattered service berry, fire cherry, beech, and yellow birch; Thunderhead sandstone substrate.

Table B-2. Composition of trees on the southwest slope of Mt. LeConte
(n = 15 prism plots at each elevation)

	Elevation (m)							
	1385		1540		1720		1845	
Mean distance to competitors (cm) ^a	864.2 (59.34)		NA ^b		NA		557.6 (36.35)	
Mean DBH Competitors (cm) ^a	56.9 (3.18)		NA		NA		31.1 (1.28)	
	Basal area (m ² /ha)							
	Absolute	Relative	Absolute	Relative	Absolute	Relative	Absolute	Relative
LIVE TREES								
<i>Picea rubens</i>	5.2	16.2	18.8	84.3	20.0	96.0	16.0	64.8
<i>Tsuga canadensis</i>	11.0	34.3						
<i>Aetula lutea</i>	10.5	32.7	3.5	15.7	0.2	0.8	0.2	0.8
<i>Quercus rubra</i>	2.2	6.8						
<i>Acer rubrum</i>	1.3	4.0						
<i>Aesculus octandra</i>	0.7	2.2						
<i>Acer pensylvanicum</i>	0.7	2.2						
<i>Prunus serotina</i>	0.3	0.9						
<i>Amelanchier arborea</i>	0.2	0.6						
<i>Abies fraseri</i>								
Total	32.1		22.3		20.9		24.7	

Table B-2. (continued)

	Elevation (m)							
	1385		1540		1720		1845	
DEAD TREES								
<i>Picea rubens</i>	0.7	53.8	2.5	100.0	0.8	3.8	1.3	5.8
<i>Quercus rubra</i>	0.3	23.1						
<i>Tsuga canadensis</i>	0.3	23.1						
<i>Abies fraseri</i>			20.2	96.2	21.2	94.2		
Total	1.3		2.5		21.0		22.5	

^an = 60 (i.e., closest living canopy or midcanopy tree in each quadrant of each cored individual); standard errors given in parentheses.

^bData not recorded.

Table B-3. Composition of trees on the northwest slope of Mt. LeConte
(n = 15 prism plots at each elevation)

	Elevation (m)							
	1385		1540		1720		1845	
Mean distance to competitors (cm) ^a	717.3 (47.96)		NA ^b		NA		557.6 (36.35)	
Mean DBH Competitors (cm) ^a	56.9 (3.18)		NA		NA		31.1 (1.28)	
	<u>Basal area (m²/ha)</u>							
	<u>Absolute</u>	<u>Relative</u>	<u>Absolute</u>	<u>Relative</u>	<u>Absolute</u>	<u>Relative</u>	<u>Absolute</u>	<u>Relative</u>
LIVE TREES:								
<i>Picea rubens</i>	9.3	23.5	12.8	100.0	11.5	97.2	18.0	55.7
<i>Tsuga canadensis</i>	16.8	42.5						
<i>Betula lutea</i>	5.2	13.2			0.2	1.4	1.0	3.1
<i>Halesia carolina</i>	4.0	10.1						
<i>Fagus grandifolia</i>	3.2	8.1						
<i>Acer rubrum</i>	0.8	2.0						
<i>Acer pensylvanicum</i>	0.7	2.2						
<i>A. pensylvanicum</i>	0.2	0.5						
<i>Prunus pensylvanica</i>					0.2	1.4		

Table B-3. (continued)

	Elevation (m)					
	1385	1540	1720	1845		
<i>Abies fraseri</i>			12.5	38.7		
<i>Sorbus americana</i>			0.8	2.5		
Total	39.5	12.8	11.8	32.3		
DEAD TREES						
<i>Picea ruben</i>	1.2	42.9	0.7	77.8	0.3	1.7
<i>Abies raseri</i>			0.2	22.2	17.5	98.3
<i>Tsuga canadensis</i>	1.3	46.4				
<i>Aesculus octandra</i>	0.3	10.7				
Total	2.8		0.9		17.8	

^an = 60 (i.e., closet living canopy or midcanopy tree in each quadrant of each cored individual); standard errors given in parentheses.

^bData not recorded.

Table B-4. Summary data for sites at which dead spruce were cored
($n = 10$ prism plots)

Elevation (m)	1675-1850
Site-specific aspect (deg.)	115-345
Inclination (%)	2-55
Mean age ^a (years)	181 (21.4)
Mean distance to competitors (cm) ^b	664.8 (58.13)
Mean dbh of competitors (cm) ^c	40.1 (2.38)
Mean dbh of cored trees (cm) ^c	46.5 (5.05)

	Basal area (m ² /ha)	
	Absolute	Relative
LIVE TREES		
<i>Picea rubens</i>	17.5	61.8
<i>Abies fraseri</i>	5.8	20.5
<i>Betula lutea</i>	5.0	17.7
Total	28.3	
DEAD TREES:		
<i>Picea rubens</i> (includes cored trees)	4.0	45.5
<i>Abies fraseri</i>	4.8	54.5
Total	8.8	
Percentage of individuals in each vigor class: ^d		
0		60.5
1		20.9
2		
3		
4 (includes cored trees)		18.6

^aBased on mean number of annual rings counted to pith or innermost annual ring observed for each cored tree ($n = 10$ per site); this does not consider possible missed annual rings due to not hitting exact center or growth occurring prior to attaining coring height; standard error given in parentheses.

^b $n = 36$ (i.e., closest living canopy or midcanopy tree in each quadrant of nine of the ten cored individuals); standard errors given in parentheses.

^c $n = 10$; standard error given in parentheses.

^dSubjective evaluation of foliage loss by all red spruce trees within prism plots using a rating scale described in the text.

Table B-5. Composition of trees at Mt. Sterling

<u>10-25 cm dbh</u>		
(Based on 4 competitors closest to each of 15 sample trees)		
Mean distance to closest competitors (cm) ^a	221.0	(12.02)
Mean dbh of closest competitors (cm) ^a	18.8	(1.19)
	<u>Number</u>	<u>Percent</u>
<i>Picea rubens</i>	33	55.0
<i>Abies fraseri</i> (living)	3	5.0
<i>Betula lutea</i>	3	5.0
<i>Sorbus americana</i>	1	1.7
<i>Abies fraseri</i> (dead)	20	33.3
<u>25-40 cm dbh</u>		Basal Area
(Based on 5 prism plots)		(m ² /ha)
	<u>Absolute</u>	<u>Relative</u>
<i>Picea rubens</i>	27.0	83.1
<i>Betula lutea</i>	0.5	1.5
<i>Abies fraseri</i> (dead)	5.0	15.4
Total	32.5	
<u>>40 cm dbh</u>		
(Based on 15 prism plots)		
<i>Picea rubens</i> (live)	20.8	68.3
<i>Betula lutea</i>	2.2	7.1
<i>Amelanchier arborea</i>	0.3	1.1
<i>Picea rubens</i> (dead)	0.3	1.1
<i>Abies fraseri</i> (dead)	6.8	22.4
Total	30.4	

^an = 60 (i.e., closest living canopy or midcanopy tree in each quadrant of each cored individual); standard errors given in parentheses.

Table B-6. Composition of trees at Norway spruce sites
(n = 8 prism plots at each elevation)
(Absolute basal area given as m²/ha)

LIVE TREES	<u>1326 m</u>		<u>1485 m</u>	
	<u>Absolute BA</u>	<u>Relative BA</u>	<u>Absolute BA</u>	<u>Relative BA</u>
<i>Picea abies</i>	7.5	35.0	25.9	85.8
<i>Halesia carolina</i>	3.4	15.9		
<i>Acer saccharum</i>	3.4	15.9		
<i>Betula lenta</i>	2.2	10.3		
<i>Fagus grandifolia</i>	1.6	7.5	2.2	7.3
<i>Acer rubrum</i>	0.9	4.2		
<i>Ilex ambigua</i>	0.6	2.8		
<i>Prunus serotina</i>	0.6	2.8		
<i>Betula lutea</i>	0.3	1.4	0.9	3.0
<i>Fraxinus americana</i>	0.3	1.4		
<i>Magnolia fraseri</i>	0.3	1.4		
<i>Prunus pennsylvanica</i>	0.3	1.4	0.6	2.0
<i>Amelanchier arborea</i>			0.6	2.0
Total	21.4		30.2	
DEAD TREES				
<i>Picea abies</i>	0.6	50.0	0.6	66.7
<i>Amelanchier arborea</i>	0.6	50.0		
<i>Prunus pennsylvanica</i>			0.3	33.3
Total		1.2		0.9

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