Abstract

Reduced growth of red spruce (Picea rubens Sarg.) has been well documented in the northeastern U.S. and southeastern Canada between the mid-1960s and mid-1980s, with unusual levels of mortality reported at high elevations. Investigation of possible causal factors has been far-reaching. Substantial research has explored the possibility that a combination of acid deposition and climatic conditions has contributed to the decline. However, there is some evidence that the reduced growth may be explainable in part by natural stand maturation and competition. We sampled 102 randomly located trees at high and low elevations on Mt. Mansfield (VT), Mt. Washington (NH), and Whiteface Mt. (NY). Radial increment mean-value functions were developed and standardized, and a temperature-based climate model was applied. Results show that red spruce radial growth has increased from a low in the early 1980s at high and low elevations. The relationship between climate and growth that prevailed from 1886 to 1960 degraded during the period 1961-1980, but returned in the period 1981-1994. Gap and interior trees showed essentially the same radial growth pattern since 1960, suggesting that competition is a relatively minor contributor to the overall trends.

Introduction

Reduced growth and unusually high mortality of red spruce (Picea rubens Sarg.) have been documented in the northeastern U.S. between the early 1960s and early 1980s (Siccama et al. 1982; Johnson and Siccama 1983; Scott et al. 1984; Hornbeck and Smith 1985; McLaughlin et al. 1987). Three large sampling efforts in the early 1980s yielded data on northeastern red spruce radial and basal area growth that have been analyzed by a number of investigators. The first is the USDA Forest Service Forest Inventory Analysis (FIA) data set, which consists of tree-ring data from 3,001 red spruce trees randomly located across Maine, New Hampshire, Vermont, and the Adirondack Mountains of New York (Hornbeck and Smith 1985). The second is the Forest Response to Anthropogenic Stress (FORAST) program (McLaughlin et al. 1983; McLaughlin et al. 1986) data set, which consists of ring width series from 2,433 red spruce, including samples from mid-elevation transects on Whiteface Mountain (NY), Mt. Mansfield (VT), and Mt. Washington (NH) (McLaughlin et al. 1987). The third data set came from trees selected at 10 elevations along horizontal transects on the east and west slopes of Mt. Mansfield, Whiteface Mountain, and Mt. Washington (Johnson et al. 1988b). Analyses of these radial and basal area increment data by a number of investigators clearly showed that growth across the northern range of red spruce had been declining since 1960. The spatial consistency of the decline suggested regional-scale influences on annual growth (Johnson et al. 1988b).

Investigations of causal factors that may have contributed to the decline have been far-reaching. Initial studies cast doubt on the possibility that biotic agents such as insects and fungal diseases were causing the decline (Johnson and McLaughlin 1986; summarized by Peart et al. 1992 and Johnson 1992), although it is likely that some organisms, including Armillaria mellea, are involved as secondary pathogens (Carey et al. 1984: Donnelly et al. 1985). Some researchers have suggested that the decline in radial growth can be attributed, at least in part, to stand dynamics (i.e., natural stand aging processes and the effects of competition) (Hornbeck et al. 1986; Federer and Hornbeck 1986; Van Deusen 1990; Reams and Huso 1990; Reams and Van Deusen 1993). These researchers have noted that the 1960-1980 growth decline appears only in tree ring-series exhibiting a 1940-1960 increase (Reams and Huso 1990), and that large-scale disturbance events, known to occur throughout the region in the 1930s and 1940s, may have initiated stand dynamics effects that are responsible for the observed growth increase (1940-1960) and subsequent decrease (1960-1980) (Reams and Van Deusen 1993). However, unusually high mortality rates (30-60% of red spruce basal area was standing dead) of red spruce near the top of its elevational range makes it clear that, at least for high elevations, stand maturation alone is not sufficient to explain the decline (Johnson et al. 1988b).

Other studies, emphasizing the regional-scale nature of the phenomenon, have implicated climatic stresses in initiating or contributing to the decline (Friedland et al. 1984; Hamburg and Cogbill 1988; Johnson et al. 1988b). Substantial research has sought to discover a link between anthropogenic pollutants and climatic factors in inducing the decline. Investigators have established that: (1) red spruce is only marginally tolerant of the extreme low temperatures typical of its habitat range (DeHayes 1992); (2) acid precipitation decreases this tolerance by as much as 10(C (DeHayes 1992; Johnson 1992); and (3) winter injury reduces the following year's basal area increment and internode length on red spruce (Tobi et al. 1995; Wilkinson 1990). In addition, widespread reports of severe winter injury for the period 1959-1962 make this factor coincident with the onset of growth decline (Johnson et al. 1988b).

It seems likely that red spruce decline is the result of multiple stressors; however, the relative importance of different stressors has not been definitively established. Disagreement remains over the role that natural stand-level processes may have played in creating the observed growth trends (Reams and Van Deusen 1993; Johnson et al. 1995; Reams and Van Deusen 1995).

More recent data from three mid-elevation sites that have been intensively studied (Mt. Mansfield (VT), Whiteface Mountain (NY), and Mt. Washington (NH)) show increased radial growth since the early 1980s (Reams and Van Deusen 1995). This trend is also evident in data collected in the late 1980s from Whiteface Mountain and other sites (G. Hawley, unpublished data; Tobi et al. 1995; Wargo et al. 1993).

In addition, by the early 1990s, deterioration of high elevation spruce appeared to have ceased at some locations (Wilmot 1994), with mortality possibly returning to lower rates (Peart et al. 1992). These findings suggest that this period of red spruce decline may have ended.

This study had three objectives: (1) to update radial and basal area growth trends for red spruce through 1995 at selected sites in the northern Appalachian and Adirondack Mountains; (2) to evaluate the role that competition may have played in the observed trends by stratifying trees based on their competitive status; and (3) to use climate modeling to help determine if the decline period has ended.

Methods

Data were collected in the summer and fall of 1996 using the sites of, and following methodologies reported by, Johnson and McLaughlin (1986). Red spruce were sampled at Mt. Mansfield (VT) (east face), Mt. Washington (NH) (east face), and Whiteface Mountain (NY) (west face). At each mountain, two sampling sites were located, one at the upper (1000 to 1220 m) and one at the lower (650 to 800 m) elevational limit of red spruce. The locations correspond to the spruce-fir and hardwood zones sampled by Johnson and Siccama (1983) and Johnson et al. (1988b). At each site, three transects were established at 50-m elevational intervals. Each transect was located along the elevational contour using an altimeter. Sampling points were established at 25-m intervals along each transect, beginning at a point randomly located along the first 25 m of the transect. At each sampling point, the nearest canopy dominant or codominant red spruce was cored using an increment borer. Two cores per tree were extracted at 1.4 m above ground surface from opposite sides of the tree, parallel to the topographic contours. Fifteen trees (3 transects of 5 trees each) were sampled at each site, for a total of 90 trees. Additional trees were sampled by extending some of the transects to ensure that sufficient numbers of trees in gap and interior classes were sampled, as will be discussed. As a result, 102 trees were sampled. Of these, 83 trees were suitable for analysis. Mean age at breast height of these trees was 133 years.

Previous studies have used variable-radius plot sampling to document changes in basal area of red spruce stands over time (Johnson and Siccama 1983; Scott et al. 1984; McLaughlin et al. 1987). These basal area data have been cited in discussions of the possible effect of competition on radial growth of sample trees (McLaughlin et al. 1987). Variable-radius plots sample larger trees with greater intensity than small trees. This technique effectively characterizes stocking and hence stand-level competition, but is not designed for estimating the competition for growing space faced by individual sample trees. Consequently, we developed and used a measure of the immediate competition from adjacent trees to assess competitive status. The rating system involved an ocular estimate of the available lateral growing space in the upper crown of each cored tree. This four-point crown exposure rating system is as follows: category 1: 75-100% of the circumference of the upper crown is free to grow laterally, i.e., without obstruction by the branches or boles of neighboring trees; category 2: 50-74% of the upper crown is thus exposed; category 3: 25-49% is exposed; and category 4: 0-24% is exposed. Many of the trees in category 1 were growing in gaps and, thus, were essentially open-grown, with no competitors for several meters in all directions. This category also included superdominants with crowns high above the main canopy. This rating system allowed for stratification of trees into gap (category 1) and interior (categories 2, 3, and 4) groups for analysis.

Cores from the 102 sample trees were mounted on wood blocks and sanded with successively finer-grit sandpaper (150, 220, 400, and 600 grit). Core preparation methods followed those of Tobi et al. (1995) using procedures outlined in greater detail by Fritts (1976) and Cook and Kairiukstis (1990). Ring widths were measured using a digital micrometer accurate to the nearest 0.01 mm. Crossdating of the sample cores to ensure accuracy of the assignment of specific years to each annual increment was done by eye (Fritts 1976) and checked using the quality control computer program COFECHA (Holmes 1983). Cores that could not be crossdated with confidence in their entirety or at least back to 1900 were eliminated from all analyses. Cores that could be crossdated but that included fewer than 70 rings were also eliminated to minimize age-related growth effects (Cook 1990). This left cores from 83 trees to be used in the analyses. Of these, 55 were considered gap trees and 28 were interior trees.

Mean annual radial increment was calculated by first computing annual means for each tree (average of the two cores). Regional means were then calculated for high (n=38 trees) and low (n=45) elevation sample sites, and 95% confidence intervals were determined. Mean annual basal area increment was calculated for each tree from mean annual radial increments. Regional basal area increment means were calculated as for radial increment means. Growth trends for gap and interior trees were compared by calculating mean annual radial increment for each stratum of trees at high and low elevations at all sites.

A repeated measures analysis of variance (ANOVA) with period (decline and post-decline) and year as trial factors (Dixon and Merdian 1992) was applied to both radial and basal area increment data sets to test whether yearly trends in growth were equal for the two periods. The decline period was defined as 1968-1981 and the post-decline period was defined as 1982-1995. Selection of the year that the post-decline period is hypothesized to have begun is based on Reams and Van Deusen's (1995) study, which found increasing growth beginning in 1982. Periods of equal years were required for the analysis, so the decline period was truncated to be equal to the hypothesized post-decline period. The statistical software BMDP 5V (Dixon and Merdian 1992) was used because it allows for this procedure to be run with data sets exhibiting autoregressive covariance structure.

The climate modeling was performed by comparing high-frequency variation (year-to-year fluctuation) in mean radial increment with high-frequency variation in values generated by a temperature-based multiple linear regression model (Cook 1987b). (For a detailed explanation of high- and low-frequency variation and filtering techniques, see Fritts 1976.) The temperature data used in developing the model were mean monthly temperatures from nearby weather stations as described by Cook et al. (1987) and Johnson et al. (1988b). This analysis was done because previous studies have shown that high-frequency variation in red spruce radial increment showed a strong relationship with high-frequency variation in climate model values until the onset of the decline period, at which point the relationship degraded (Cook 1987b; Johnson et al. 1988b).

To remove low-frequency variation, the mean annual regional radial increment data were high-pass filtered (Fritts 1976) using first-differencing. Each differenced value simply represents the change in mean ring width from one year to the next (Cook et al. 1990). The resulting value is referred to as a tree-ring index. The regression equation developed by Cook (1987b) was used to develop temperature model values from regional monthly mean temperatures; the temperature model values were developed specifically to test for correlation with tree-ring indices as a means of assessing the relationship between temperature and growth. This data set was also high-pass filtered using first-differencing. Regression analysis was then used to determine the relationship between high-frequency variation in mean annual radial increment (tree-ring indices) and high-frequency variation in temperature model values.

The tree-ring indices were compared to temperature model values for four time periods: 1885-1940, 1941-1960, 1961-1980, and 1981-1994. Because the model was calibrated using other data sets (Cook 1987b), all four periods were considered verification periods (Fritts 1976). This allowed for a direct test of stability of the relationship between the temperature model values and tree-ring indices (Fritts 1976). The periods were chosen specifically to test the historic, pre-decline, decline, and possible post-decline responses of red spruce to climate, and were based on periods used in a similar analysis by Cook et al. (1987).

Results

Red spruce radial growth, after declining steadily from 1960 to the early 1980s, increased slightly at both high and low elevations after 1982 (Figure 1). The ANOVA results show that trends in annual radial increment for hypothesized decline (1968-1981) and post-decline (1982-1995) periods were significantly different (p<.01). This is consistent with reports that symptoms of decline of red spruce in the Northeast may have abated since the late 1980s (Reams and Van Deusen 1995; Wilmot 1994; Peart et al. 1992). Basal area increment trends show essentially the same pattern as the radial increment trends (Figure 2),

and the ANOVA results indicate that trends for hypothesized decline and post-decline periods were also significantly different (p<.01).

The effect of exogenous disturbance is clearly evident in the low elevation mean radial increment plot (Figure 1). In 1895, sampled red spruce in these low elevation stands began a period of dramatically increased growth. These stands had recently been logged, releasing the suppressed advance regeneration and allowing rapid growth (Johnson et al. 1988b). This growth surge appears to be absent from the high elevation stands (Figure 1) because these stands, as far as historical documents and current age-class distributions show, have never been logged (Battles et al. 1992).

Gap and interior trees showed similar radial growth trends (Figure 3). All three low-frequency variation phenomena of interest (1940-1960 increase, 1960-1980 decrease, and 1980-1995 modest increase) are evident in both gap and interior mean radial growth for both high and low elevations. At high elevations, gap and interior growth rates have been nearly identical since around 1940. In contrast, at low elevations, interior growth rates have been consistently lower than gap growth rates since 1900. This supports the contention that, at high elevation, any competitive advantage conferred on gap trees may be offset by the climatic stressors (e.g. wind, rime ice loading, temperature extremes; see LeBlanc 1990) to which these trees are exposed.

Regression of tree-ring indices and temperature model values yielded the following p-values for the four verification periods: 1886-1940 (high elevation p<.001, low elevation p<.02), 1941-1960 (high elevation p<.001, low elevation p<.001), 1961-1980 (high elevation p>.1, low elevation p>.2), and 1981-1994 (high elevation p<.1, low elevation p<.1) (Figure 4).
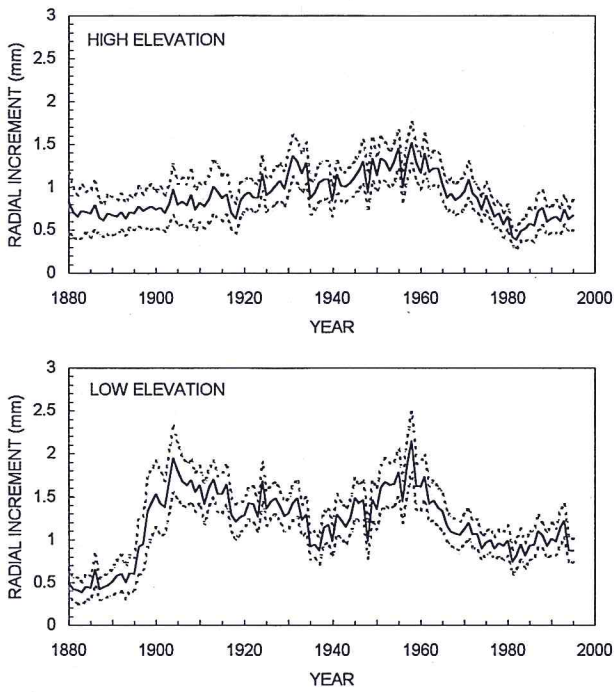
Figure 1. Mean annual radial growth of red spruce. Trees are from high (N=38) and low (N=45) elevations on Mt. Mansfield (VT), Mt. Washington (NH), and Whiteface Mt. (NY). Dashed lines indicate 95% confidence interval (+/- 2 standard errors of the mean). Only trees >70 years old were used in the analyses; sample size prior to 1925 is variable.
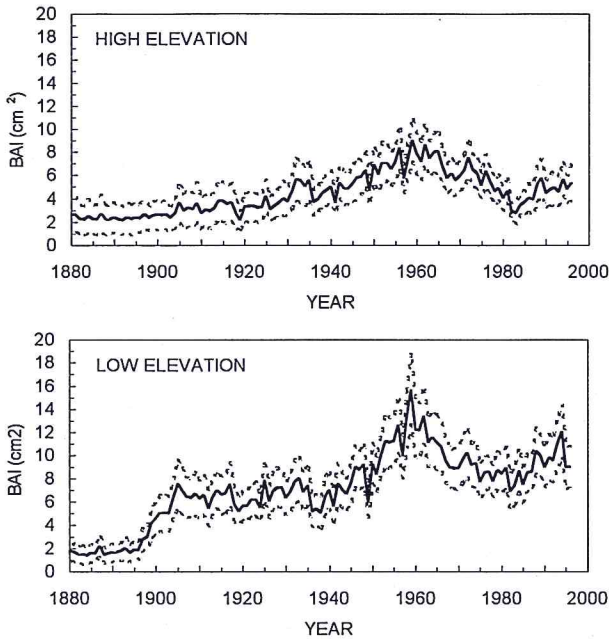
Figure 1 - Sims, Cook, Johnson, and Donnelly

Figure 2. Mean annual basal area increment of red spruce.
Details as in Figure 1.
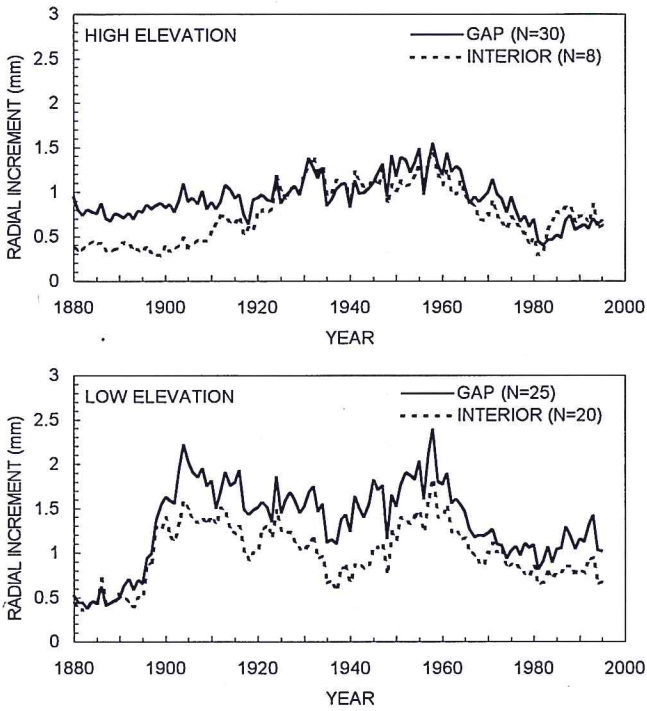
Figure 2 - Sims, Cook, Johnson, and Donnelly

Figure 3. Mean annual radial growth of red spruce, stratified by crown exposure rating. See text for explanation of rating system. Other details as in Figure 1.

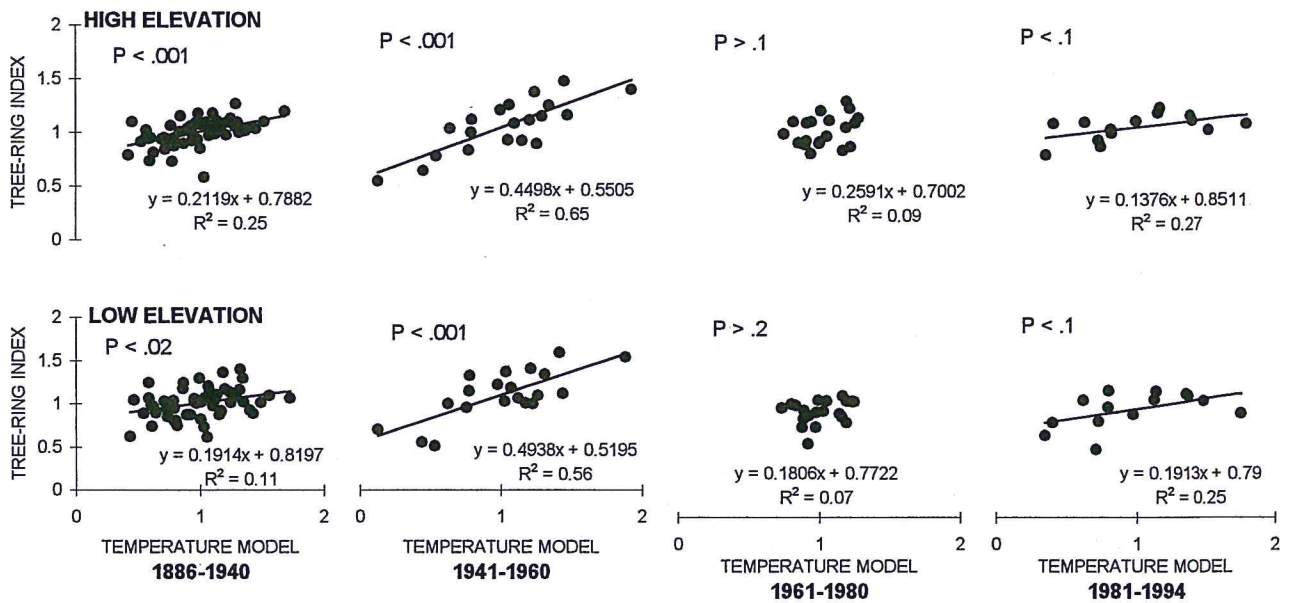Figure 3 - Sims, Cook, Johnson, and Donnelly

Figure 4. Regression of tree-ring indices and temperature model values over four verification periods. Tree-ring indices are first-differences of mean annual radial growth across all sites. Temperature mode values are first-differences of values from a multiple linear regression equation developed by Cook (1987b), which is based on regional monthly mean temperatures. Tree-ring indices and temperature model values have been scaled to a mean of 1.0 by addition of a constant.

Figure 4 - Sims, Cook, Johnson, and Donnelly

Discussion

Climate

Results of the regression analyses suggest that the sample trees have begun to reestablish the relationship with climate that held from 1886 to 1960 but was lost between 1961 and 1980. Although the p-values for the post-decline period (1981-1994) are higher than in the two pre-decline periods, this may be due in part to the fact that only 14 years are included, which reduces the power of the test in detecting significance.

The possibility remains that these results are influenced by differing levels of variability in the data among the four periods. For example, the data points in the decline period appear to fall within a narrower range than the data in the other three periods (Figure 4). To determine if lack of variability is influencing the results, Spearman's rank correlation test was applied. Data were first transformed by replacing the actual values with their ranks within each period; next, the data were regressed as in the parametric analysis (Figure 4). This has the effect of equalizing the within-period variation among all periods (Figure 5). The resulting p-values (Figure 5) correspond well with the p-values from the parametric analysis (Figure 4), suggesting that differing levels of variability in the data is not influencing the results.

Additional exploratory data analysis suggests that the period of anomalous radial growth decline for red spruce in the Northeast may in fact be limited to 1960-1974. By testing different decline and post-decline periods, we discovered that 1960-1974 is the period with the weakest relationship between climate and growth (high elevation p>.5, low elevation p>.5). Using these modified verification periods, the post-decline period (1975-1994) showed significant relationships between climate and growth (high elevation p<.02, low elevation p<.02). This exploratory finding is consistent with studies that predate evidence of the abatement of decline in red spruce radial growth, which suggested that, by the late 1970s, trees may have resumed a normal response to climate after a period of shock (Johnson et al. 1988a).

These results are consistent with the winter injury/acid precipitation hypothesis for the decline, since widespread severe winter injury is documented for red spruce from 1959-1965 almost annually throughout the Northeast (Johnson et al. 1988b). This establishes the necessary initiating stress for a decline episode (Manion 1981). In addition, winter temperatures figured prominently in the climate model used: low temperature in the previous December was among the best predictors of low annual growth the following year (Cook 1987b). However, the fact that winter injury occurred several times in the 1980s and early 1990s (Tobi et al. 1995) at the same time that red spruce radial growth was increasing throughout the region must be explained (Reams and Van Deusen 1995). One plausible explanation advanced by Johnson et al. (1992) and Johnson et al. (1996) is that the trees that died in the 1960s, 1970s and early 1980s had been stressed past a critical threshold beyond which carbon available for defense and repair was insufficient to compensate for the initiating stress. The remaining trees were able to recover from this period of unusual stress and resume normal growth. Under this explanation, either the winter injury that occurred in the 1980s and early 1990s was not as severe in its effects as the events that occurred in 1959-1965, or the trees that survived the period of decline and mortality possessed some advantage, genetic or otherwise, which rendered the winter injury less effective in interfering with carbon allocation for growth, defense, and repair. Further explanation may lie in the fact that winter injury occurred over several consecutive years in 1959-1965, while during the 1980s and 1990s injury years were not consecutive.

Disturbance

Cook (1985; 1987a) developed a linear aggregate model to describe hypothetical ringwidth series and allow application of tree-ring analysis techniques, typically developed for open-grown trees, to forest interior trees. According to this model, the climate signal inherent in a tree-ring series from a shade-tolerant, closed-canopy species such as red spruce can be contaminated by error, growth trend, exogenous disturbance, and endogenous disturbance. Exogenous, or stand-wide, disturbance, is assumed to be detectable in all or most of the trees in a stand or across a region. The 1895 logging event, evident in tree-ring series from low elevation stands sampled in this study, is an example of an exogenous

disturbance simultaneously affecting the growth rates of most trees in a stand. Endogenous disturbance encompasses tree mortality at the individual or small-group scale, and subsequent increased availability of growing space only for adjacent trees. For purposes of developing this approach to standardizing tree-ring series that may be subject to suppression-release patterns and other effects of competition, these phenomena are assumed to be randomly distributed in space and time (White 1979; Oliver and Larson 1990). Van Deusen (1990) correctly notes that mean growth trends may mask the fact that some trees in a group are being released and others are not. The approach used here assumes that exogenous disturbances are unambiguous and can be removed from the analysis, while the remaining endogenous disturbance pulses are random and hence will not materially affect the mean series. Reams and Van Deusen (1993) present the view that either: (1) an unusually large number of exogenous disturbances were affecting the region in the 1930s and 1940s; or (2) the rate of endogenous disturbance was unusually high in this period due to a combination of disease and climate stressors. Reams and Van Deusen (1993) attribute the increase in radial growth that occurred between 1940 and 1960 (Figure 1) to a series of large-scale disturbances that occurred throughout the northeastern U.S. between the 1930s and about 1950. These disturbance events include the 1938 hurricane, beech bark disease, and birch dieback. Reams and Van Deusen (1993) also found that initiation of the 1960-1980 decline appeared to be conditional on the 1940-1960 increase.

We tested the hypothesis that disturbance events were responsible for the 1940-1960 increase and 1960-1980 decrease in radial growth by applying the methodology of Lorimer and Frelich (1989). This method involves the examination of radial growth of individual trees to determine if release has occurred. We examined individual, unstandardized tree-ring series to determine which trees may have been released during the period 1930-1949. Inferring release events with certainty from tree-ring data is difficult at best; Lorimer and Frelich's methodology provides a means of at least partially eliminating subjectivity from the analysis. All tree-ring series that met Lorimer and Frelich's criteria for major (increase of (100% in annual radial increment) or moderate (increase of 50-99% in annual radial increment) release, for either a sustained ((15 yr) or temporary (10-15 yr) time period beginning between 1930 and 1949, were considered "release" series. Those that did not meet the criteria were considered "no-release" series.

A comparison of the release and no-release mean growth trends (Figure 6) lends credence to the notion that some trees were released by disturbance events in the 1930s and 1940s, although it clearly cannot unequivocally establish the type, size, or intensity of these conjectured disturbance events, or even provide a rigorous test of the hypothesis that they occurred. Prior to about 1940, these trees were growing at a slower rate than the no-release trees, suggesting that they were relatively suppressed. Between 1940 and 1960, the radial growth rate of these trees more than tripled, followed by a nearly symmetrical reduction between 1960 and 1980. However, the no-release trees, which showed essentially stable growth between 1920 and 1960, also underwent a major and sustained decrease in growth between 1960 and 1980. These trees, which show no release effect from disturbance events in the 1930s and 1940s, nevertheless exhibit the post-1960 decline phenomenon (Figure 6). This analysis suggests that, while large-scale disturbance events may have shaped the growth trends of red spruce to some extent by creating a 1940-1960 increase, suppression-release phenomena have only exacerbated a 1960-1980 decrease which appears to be due primarily to factors other than stand dynamics.

The foregoing notwithstanding, there are several conceptual problems with the use of tree-ring data to infer the occurrence of disturbance events. The first is that inferring disturbance events, regardless of the technique used, is inherently conjectural without corroborating evidence that the specific stands sampled were disturbed by specific events. Reams and Van Deusen (1993) present evidence that forests in the northeastern U.S. have been subject to frequent canopy disturbances from wind events, disease outbreaks, and logging throughout the twentieth century, with an apparent concentration of disturbance events in the 1930s and 1940s. Nevertheless, there remains a lack of evidence confirming that any of these disturbance events actually killed trees in the stands studied, despite the fact that it is likely to have occurred to some degree.

Second, while the 1938 hurricane is temporally distinct, the other disturbance events appear to be somewhat artificially synchronized to explain the 1940-1960 growth increase. In fact, the disease epidemics cited by Reams and Van Deusen (1993) as synchronizing factors in the 1940-1960 growth increase occurred gradually over a period of several decades. The killing front of beech bark disease, for example, took approximately 50 years (1920-1970) to spread from Nova Scotia to southern New England and northern New York, and the disease is still causing mortality in beech stands in the Northeast (Tainter and Baker 1996; Shigo 1972). Birch dieback occurred extensively in the Northeast from the 1930s through 1959 (Millers et al. 1989). Since that time it has occurred sporadically in localized areas of the Northeast (Millers et al. 1989).

Third, and perhaps most important, if concentrated canopy disturbance occurred to the extent that it is responsible for the dramatic growth increase (1940-1960) and subsequent decrease (1960-1980) seen in mean radial increment data for red spruce in the Northeast, similar patterns attributable to stand dynamics should be expected for associated tree species. Hornbeck et al. (1988) developed regional growth curves for 10 species in New England for the period 1950-1980 and found that only red spruce and balsam fir exhibited a decline after 1960. The other eight species (eastern hemlock, yellow birch, sugar maple, American beech, white ash, red maple, red oak, and white pine), several of which co-occur with red spruce throughout much of its range in New England, all show increasing growth during this period.

Competition

The results presented here show that red spruce growing essentially free from competition have exhibited the same low-frequency variation phenomena (growth trends) over the past 50 years as do trees growing in forest interior settings with varying degrees of competition. Linking either the 1940-1960 increase or the 1960-1980 decrease to competitive status is tenuous, since trees across the full range of competitive status exhibit both phenomena. This is consistent with numerous studies that have specifically examined the role that competition may have played in contributing to the decline (LeBlanc 1990; LeBlanc 1992; McLaughlin et al. 1987; Johnson and McLaughlin 1986).

Conclusions

Evidence presented here suggests that the reduced radial growth component of the red spruce decline syndrome in the northeastern U.S. has abated at three mountains that have been intensively studied. Regression of temperature model values and tree-ring indices suggests that the relationship between climate and growth that prevailed from 1886 to 1960 was disrupted during 1961-1980. Since 1981, this relationship has strengthened. This suggests that the period of anomalous growth decline for red spruce at Mt. Mansfield (VT), Mt. Washington (NH), and Whiteface Mountain (NY) has ended. Additional exploratory analysis suggests that the period of truly anomalous growth may in fact be limited to 1960-1974. These findings are consistent with the acidic precipitation/winter injury hypothesis for red spruce decline, since winter temperatures figure prominently in the climate model used. Trees that failed to crossdate were not included in any analyses, which represents a limitation common to all tree-ring studies. In addition, because only live trees were sampled, trees that failed to survive the recent widespread mortality episode were not analyzed. The value of the information lost by excluding these trees is not known.

Red spruce currently growing in the forest interior surrounded by competitors for light and growing space showed essentially the same growth trends over the past 50 years as red spruce trees currently growing in gaps. No attempt was made to evaluate past competitive conditions. Suppression-release patterns in individual tree-ring series clearly show the role of disturbance events in influencing overall trends, but the post-1960 decline and post-1980 increase are present in trees without evidence of release in the 1930s and 1940s. Because competitive status and the effects of disturbance cannot account for all of the low-frequency variation in radial growth rates observed, we conclude that other factors may play a more significant role in the long-term radial growth trends of red spruce than previously believed.

We agree with the observations of LeBlanc (1993) that the ongoing debate over the nature and cause of red spruce decline is valuable. We believe it continues to refine our understanding of the concepts of forest health and forest decline and yields insight into how elements of these sometimes elusive concepts might be most appropriately measured.
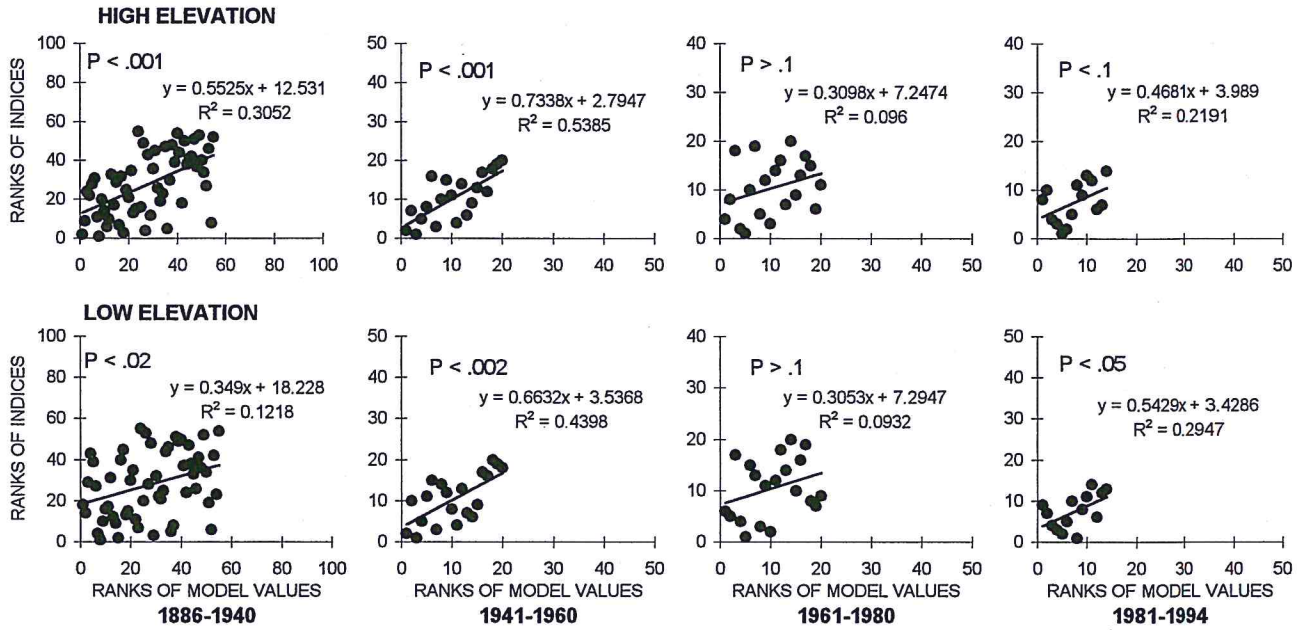
Figure 5. Spearman's rank correlation of tree-ring indices and temperature model values. All values were first standardized as in Figure 4, then transformed by ranking within each verification period.

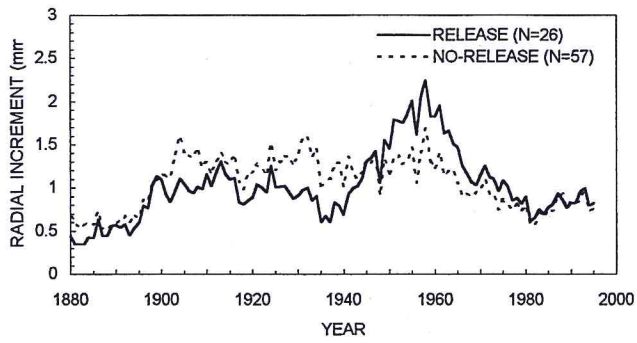Figure 5 - Sims, Cook, Johnson, and Donnelly

Figure 6. Mean annual radial growth for red spruce, classified by release category. See text for definition of categories. Other details as in Figure 1.

Figure 6 - Sims, Cook, Johnson, and Donnelly

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Acknowledgements

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