Long-term growth trends of red spruce and fraser fir at Mt. Rogers, Virginia and Mt. Mitchell, North Carolina

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Abstract

Cross-sectional area growth and height growth of Fraser fir and red spruce trees growing in Virginia and North Carolina were analyzed to identify possible long-term growth trends. Cross-sectional area growth provided no evidence of growth decline. The individual discs were classified according to parameter estimates of the growth trend equation. The predominant pattern of growth was a steady increase followed by fluctuation about a horizontal line. Other cross-sections exhibited a steady increase throughout the series. The only discs that represent declining growth patterns were from trees in subordinate crown position or which had previous top damage. No unexplained growth decline was present in any disc. The results regarding height growth were uncertain. A slight decline in height growth was present although we suggest that this observation was due to problems with the data or the model used to fit height growth. These findings contradict other studies suggesting that a recent growth decline has occurred in red spruce in the southern Appalachians. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Large-scale tree mortality and growth declines have occurred in Europe, Asia, the Pacific rim, and Eastern United States within the last 20 years (McLaughlin, 1985; Schutt and Cowling, 1985; Mueller-Dombois, 1986; Cook and Zedaker, 1992; Peart et al., 1992; Skelly and Innes, 1994). Although numerous hypotheses exist, the factors causing these effects are not known; the causes are likely to be unique to a specific forest-type and a specific site (Skelly and Innes, 1994). There is evidence that some observed growth declines have more recently been reversed (Kenk, 1990; Reams et al., 1993; Skelly and Innes, 1994).

High elevation red spruce (*Picea rubens Sarg.)* and Fraser fir (*Abies Fraseri* (Pursh) Poir.) forests in the southeast United States are among those forests that may have incurred a recent episode of increased tree mortality along with other symptoms such as premature needle loss. Barnard et al. (1990) indicate that the current consensus implicates mortality to Fraser fir

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from balsam wooly adelgid (*Adelges piceae* (Ratzeburg)) as a primary cause which produces exposure or winter desiccation damage to red spruce. Although aluminum levels are often high in the soils, aluminum concentration was not found to be related to the decline. Johnson et al. (1991) indicate that red spruce forests in the Great Smoky Mountains are under stress, as evidenced by high soil solution aluminum levels and high nitrate leaching rates. However, they did not indicate that these stresses were caused by atmospheric inputs, nor did they indicate that the stresses would cause a dieback or growth decline. We consider long-term trends of growth for red spruce and Fraser fir at Mt. Rogers, VA and Mt. Mitchell, NC. There is high mortality in the fir population at Mt. Mitchell caused by balsam wooly adelgid; mortality due to balsam wooly adelgid is rare at Mt. Rogers.

2. Methods

2.1. *Data collection*

The data collected for this study were associated with another study aimed at describing the red spruce and Fraser fir stands on Mt. Rogers, VA and Mt. Mitchell, NC (Nicholas et al., 1992). Destructive plots were located adjacent to permanent plots used to describe the vegetation. The vegetation plots were randomly located to fill four elevation classes (5000, 5500, 6000 and 6500 ft asl; 6500 class was absent at Mt. Rogers), two aspects (West and East) and three physiographic locations (ridge, slope and draw) for each mountain range. The West aspect (NW to SW) reflects the aspects exposed to prevailing winds. The East aspect (NE to SE) reflects aspects protected from prevailing winds. Some of the cells could not be filled with a stand; suitable stands were not present. Many of the vegetation plots were in a natural area and no destructive sampling could be conducted.

Eighteen destructively sampled plots were installed. One tree each of red spruce and Fraser fir was randomly selected for stem analysis from among those that were in dominant or co-dominant crown classes, when such trees were present in the stand. Other red spruce or Fraser fir trees were randomly selected for stem analysis, regardless of crown class. Height measurements were taken on all trees destined to be

harvested. Stem analysis was carried out by felling the tree, sectioning at 1.37 and at 2 m intervals above 1.37 m until a 5 cm stem diameter was reached. Above this level, internodes were measured to the tip of the tree. Photographs were taken of each disc and growth rings were digitized using a procedure tested by Goelz and Burk (1987).

Within the 18 plots, 58 trees were harvested. Forty-five were red spruce and 13 were Fraser fir. Most trees were from elevations of 5000 or 5500 ft asl. At these elevations, the destructive plots were distributed on the ridge, slope or draw physiographic locations. The inside bark diameter at breast height varied from 5.67 to 42.37 cm. Height varied from 3.64 to 24.17 m. The youngest tree was 17 years old from stump height, the oldest was 139. As spruce and fir seedlings may grow very slowly, the total age is several years older than the number of rings at stump height (0.06-0.5 m). There were more destructive plots located on the protected aspect (eastern) than exposed the aspect (western). Although vegetation sample plots were equally allocated to all elevation by aspect by physiographic site combinations (when available), many of the plots fell within wilderness areas where destructive sampling was not allowed.

Two radii on each photograph were digitized. If the two radii gave conflicting ages, the radii were digitized a second time. Plotting of the ring widths for different radii and comparing them to the photograph often illuminated the reason for a discrepancy, that is, a false or missing ring on one of the radii. Formal cross-dating of the ring-width series was not carried out, although visual correspondence between two radii on the same disc was investigated. Thus, cross-dating was carried out within a disc rather than among all discs for all trees. As we digitized from photographs of one-quarter to all of the disc, we could identify false or partially absent rings much more easily than if we had used individual tree cores; thus we minimized the need for cross-dating. We consistently observed narrow rings associated with drought periods identified by McLaughlin et al. (1987); thus ages were correct.

2.2. *Standardization of ring increment*

The intent of standardization is to produce a series of mean and stable variances; this is generally done by dividing observed growth by predicted growth. Var-

ious functions have been used to fit an equation-relating ring increment to age. Either radial increment or cross-sectional area increment has been used as the dependent variable for the regression. Although we fit an equation to the radial increment of individual discs, we chose to concentrate on cross-sectional area increment, as radial increment is known to decline with age, thus obscuring whether the decrease is due to ontogeny or some extrinsic factor (Phipps and Whiton, 1988). We used Hoerl's special functions (Daniel and Wood, 1980) to describe the trend of growth as have Warren (1980) and Monserud (1986). The form of this equation is:

$$g = \alpha t^{\beta} e^{c}$$ (1)

In this equation g is annual growth in radius or cross-sectional area, t is number of rings from the pith, e is the base of the natural logarithms, and α, β and c are parameters to be estimated. The equation may be linearized by taking natural logarithms of both sides and thus may be fit by linear regression techniques. Linearization implies multiplicative lognormal errors on the natural scale. This function is very flexible and may describe the curves of many shapes. Examples of fitted lines are given in Fig. 1. The function may also produce the shape of a negative exponential, although that growth pattern was not observed for any of our discs. Warren (1980) restricted c to be negative; we did not. Some discs displayed patterns approaching expo-

nential rather than negative exponential. Although Eq. (1) is very flexible, it does not estimate a growth trend well when there is an abrupt change in the data. If a tree has been released from competition, or if growth has abruptly accelerated or decreased due to any cause, the equation does not fit well in the region of the abrupt change. However, this is true for any continuous function. As we use the ring index in our figures to supplement the pattern depicted by raw ring increments, it will be clear where abrupt changes occurred and the reader may discount year-to-year differences in the ring index in the region of the abrupt change.

For cross-sectional area increment, Eq. (1) was fit by both ordinary least squares and generalized least squares under an assumption of first-order autocorrelation. The generalized least squares estimates are somewhat more efficient than the ordinary least squares estimates and the variances of the ordinary least squares estimates are biased when autocorrelation is present (Wonnacott and Wonnacott, 1979). The bias of variance implies that confidence intervals or tests of significance of the parameters will have true error rates that are lesser than the nominal error rates, to an unknown degree. This will have important consequences if significance tests determine whether a parameter will be included in the final fitted model or if a given parameter is used to indicate a growth decline. The generalized least squares was carried out by the method of generalized differences, as described in Wonnacott and Wonnacott (1979).

Once the equation was fit for each individual disc, indices were derived based on the relationship between observed growth and predicted growth. Listed below are two indices that we calculated.

$$I_1 = \frac{O_i}{P_i}$$ (2a)

$$I_2 = 1.0 + \frac{((e_i) - \rho^{*}(e_{i-1}))}{P_i}$$ (2b)

Where I_1 and I_2 are the indices, O_i is the observed growth at time i, P_i represents the predicted growth at time i, e, is the raw residual at time i, e_{i-1} is the residual at time i-l (and thus the numerator of Eq. (2b) is the autocorrelation residual or white noise)) and ρ is the autocorrelation coefficient. Index 1 is the typical index used in dendrochronology. Index 2 is an autoregressive form of index 1. Index 2 is based
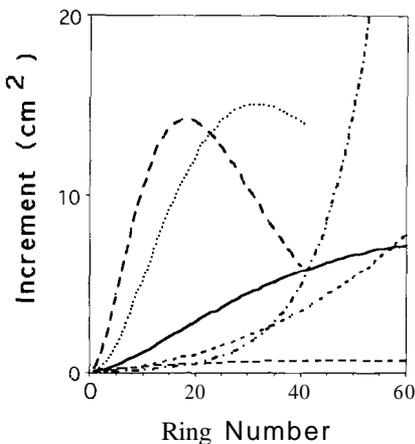

Fig. 1. Examples of Hoerl's function. The six lines represent Hoerl's function fitted to individual discs. Ring number originates at the pith and proceeds to the cambium.

on the observation that index 1 is equivalent to a residual scaled by predicted growth and added to 1, thus Eq. (2a) may be written as:

$$I_1 = \frac{O_i - P_i}{P_i} + 1 \qquad (2c)$$

The numerator of Eq. (2c) is a normal residual. In Eq. (2b), the autoregressive index replaces the ordinary residual with an autoregressive residual. The indices provided by Eq. (2b) followed the same trends as the indices provided by Eq. (2a). However, the fluctuations were dampened. As the trends of both indices followed the same pattern, we only provide the standard indices calculated by Eq. (2a). The index calculated by Eq. (2b) may be preferred when inferences are made regarding year-to-year variability in growth (e.g. climatic influence), but the index calculated by Eq. (2a) may be more appropriate when long-term trends are investigated.

2.3. *Height growth data*

Each tree provided several discs and each disc provided an age at a given height. The Carmean (1972) method was used to estimate the total height associated with a given section height. Dyer and Bailey (1987) found this method to be best among several alternatives. Internode measurements were also taken above the highest section point for each tree. Unfortunately, internodes were extremely difficult to identify in the field as the number of observed internodes did not correspond with the number of rings at the highest section point. The number of observed internodes exceeded the number of rings by a factor of two for some trees and was one-fourth the number of rings for other trees. Where the number of observed internodes equalled the number of rings, additional data points were obtained. Total height at total age provided one additional measurement point for each tree.

2.4. *Height growth model*

Two base models were fit to the data: a difference form of the Schumacher equation and a difference form of Richards' function. We chose to use difference forms because height-growth equations typically include site index or some other variable related to

growth rates. By using a difference form we were able to utilize past growth as an indicator of future growth.

The difference form of the Schumacher equation may be written as:

$$\ln(H_2) - \ln(H_1) = \beta\left(\frac{1}{A_2} - \frac{1}{A_1}\right) \qquad (3)$$

H_2 is height at age 2, A_2, H_1 is the initial height at age A_1 and β is a parameter to be estimated. As initial fits to this model were poor, we tried to expand the model using additional terms on the right hand side.

The difference form of Richards' function may be written as:

$$H_2 = H_1\left(\frac{(1 - e^{\theta A_2})}{(1 - e^{\theta A_1})}\right)^{\beta} \qquad (4)$$

In Eq. (4), θ represents a parameter, the other symbols are as defined above. This form of Richards' function performed poorly, as the shape of the growth curve was assumed constant for all trees. Thus the difference form was expanded by solving for β and replacing into the equation to obtain:

$$H_2 = H_1\left(\frac{1 - e^{\theta A_2}}{1 - e^{\theta A_1}}\right)^{\left(\frac{\ln\left(\frac{H_1}{H_0}\right)}{\ln\left(\frac{1 - e^{\theta A_1}}{1 - e^{\theta A_0}}\right)}\right)} \qquad (5)$$

In this form, H_2 is height at some future age, A_2. H_1 and A_1 are current height and age and H_0 and A_0 are the first height and age measurement, typically stump-height. This equation is a second-order difference equation. Indices are not needed with regard to height growth as the variance is stable.

3. **Results and discussion**

3.1. *Cross-sectional increment*

Discs were taken at multiple points on the same stem for two reasons: (1) ring counts at various heights along the stem provided ages at each height for height growth modeling, and (2) it was believed that upper stem cross-sectional increments might be more informative than breast height measurements (LeBlanc et al., 1987). However, upper stem growth did not appear to be any more responsive than breast height stem growth. In Fig. 2, cross-sectional area increment is
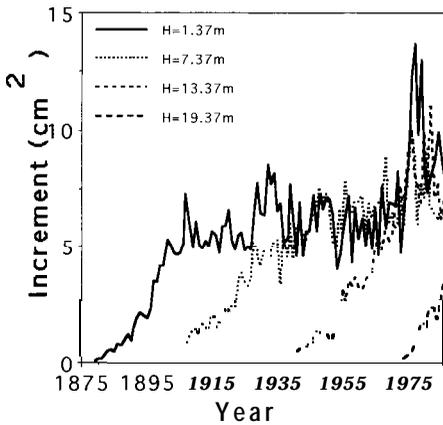
Fig. 2. Cross-sectional area increment is plotted for four discs arising from the same tree. The four discs are: breast height (1.37, 7.37, 13.37 and 19.37 m) from the base of the tree.
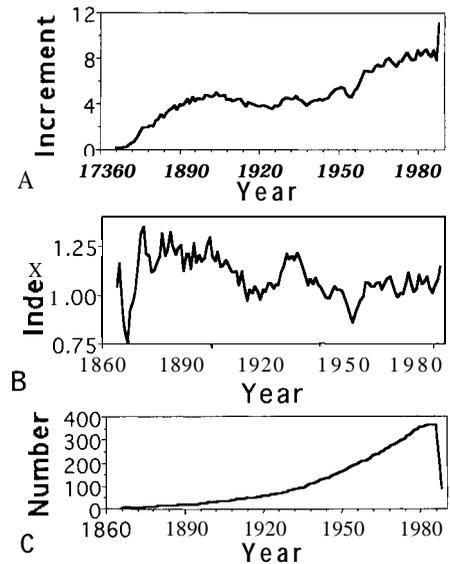

Fig. 3. For all discs regardless of species, average values of cross-sectional area increment and ring index are plotted against year. Area increment is in cm^2 and is plotted in (A). Ring index is plotted in (B) and the number of discs is plotted against year in (C).

related to year for four discs from a single tree. Regardless of height, area increment increases to a given level then fluctuates about that level. It appears almost as if the lower discs are shifted to the right and truncated to form the upper discs; this pattern is typical. This would imply that upper crown discs are not necessary to determine the cross-sectional area growth patterns under normal circumstances. LeBlanc (1990) indicated that breast-height growth indices were strongly related to whole-stem growth indices and thus breast-height growth was a valid index of vigor. We do not imply that our observation applies in other situations; it would not be true for very slowly growing trees that, in some years, only form annual rings on the stem within the live crown.

The differences between parameter estimates from ordinary least squares and generalized least squares were small. Occasionally, the significance of a parameter would differ between the fitting methods. A parameter might be significant by ordinary least squares and insignificant by generalized least squares; the reverse was also true. As the results between the two methods are similar, only the generalized least squares results will be presented.

Fig. 3 contains graphs for all data combined. Although there is considerable high-frequency variability, the trend is generally of increasing area increment. A low point around 1953-1954 was observed in almost all discs; this was identified as a drought period by McLaughlin et al. (1987). The abrupt increase in

the average area increment and average ring index from 1985 to 1987 is largely an artifact of sampling. The 10 trees harvested in 1988 tended to have above-average growth rates. As trees harvested in 1986 and 1987 were no longer averaged with the 1988 trees, the average growth rate appeared to increase.

Average increment and indices are given for all red spruce data in Fig. 4. As most of the destructively sampled trees were red spruce, the graph is very similar to that of Fig. 3. Data for Fraser fir is plotted in Fig. 5. Although the data comprised relatively few discs, the trend is clear. Cross-sectional area increment increases and then fluctuates about a level. The abrupt decline from 1985 to 1986 is again an artifact of sampling.

As the preceding figures include average cross-sectional increments and indices across all discs for a species, variation among trees is masked. As some subset of the data may indicate a growth pattern that differs from the rest of the data, we used cluster analysis to identify subsets. The spruce discs were clustered according to the generalized least squares parameters. The integrated distance between two fitted lines was used as the distance measure between two discs for cluster analysis. The area between the two
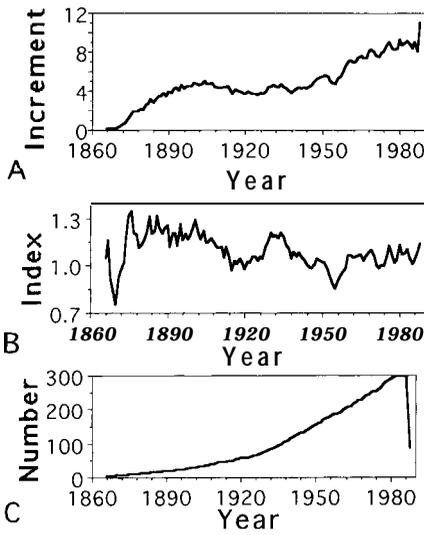
Fig. 4. For all red spruce discs, average values of cross-sectional area increment and ring index are plotted against year. Area increment is in cm² and plotted in (A). **Ring** index is plotted in (B), and the number of discs is plotted against year in (C).

fitted lines was integrated from ring one to the maximum age of the youngest of the two discs.

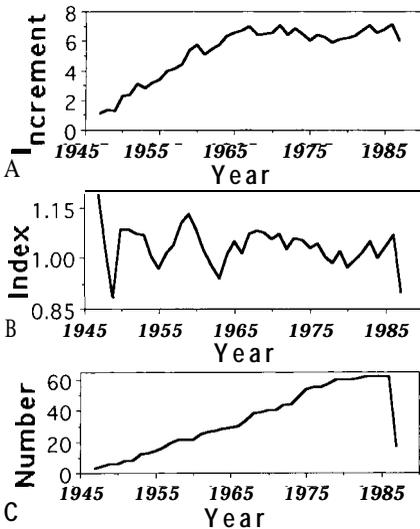The spruce data were divided into five classes. The relationship between the classes and position in the

Fig. 5. For all Fraser fir discs. the average of cross-sectional area increment and ring index are plotted against year. Area increment is in cm² and is plotted in (A). Ring index is plotted in (B). In (C), the number of discs is plotted against year.
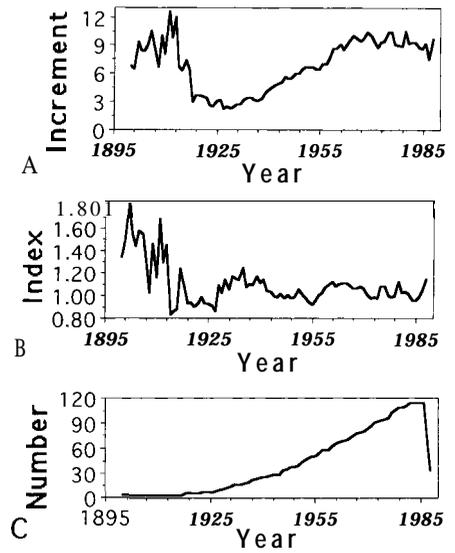

Fig. 6. For all discs belonging to spruce class one formed by cluster analysis, the average of cross-sectional area increment and ring index are plotted against year. Area increment is in cm² and is plotted in (A). Ring index is plotted in (B). In (C), the number of discs is plotted against year.

stem was weak; no class had a preponderance of lower or upper stem discs. Within a tree, most of the discs would occur in the same group, although this was not always the case. A tree that had been released from suppression would often have lower discs in one group and the discs from higher on the stem in another group.

Average area increment and the indices for spruce class one are shown in Fig. 6. A drastic decrease occurred before 1915, but this reflects the presence of only one tree before this time. Although the c parameter of Eq. (1) was negative for this group, there is no other noticeable decrease in growth.

The second group of red spruce discs also possessed a negative c parameter. Fig. 7 includes the average area increment and ring index for class two. The area increment indicates a slight increase in growth rate since the mid-1950s. This trend is barely evident for the index.

The c parameter for the third class for red spruce was positive. Thus, area increment generally increases (Fig. 8). The two large spikes at around 1890 and 1930 are caused by large residuals occurring when trees are released from competition. Eq. (1) cannot satisfactorily model abrupt release and this inadequacy pro-
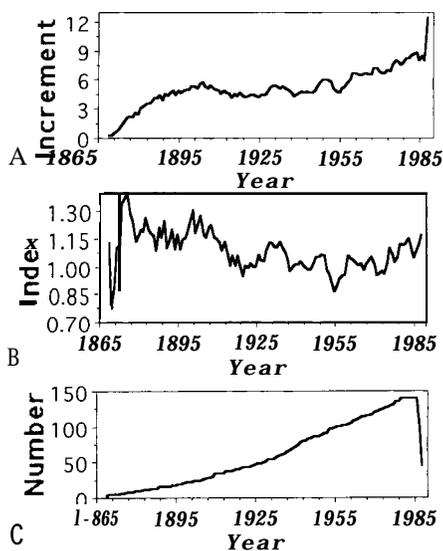
Fig. 7. For all discs belonging to spruce class two formed by cluster analysis, average of cross-sectional area increment and ring index are plotted against year. Area increment is in cm' and is plotted in (A). Ring index is plotted in (B). In (C), the number of discs is plotted against year.

duces large indices. As there were few discs in this class that were older than 50 years, the pattern of release in one or two discs can overwhelm the average
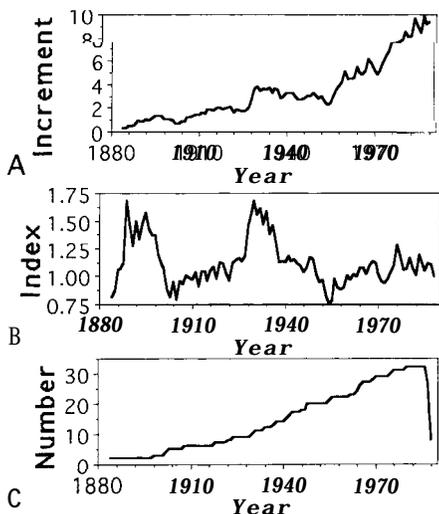

Fig. 8. For all discs belonging to spruce class three formed by cluster analysis, average of cross-sectional area increment and ring index are plotted against year. Area increment is in cm' and is plotted against year. Ring index is plotted in (B). In (C), the number of discs is plotted against year.
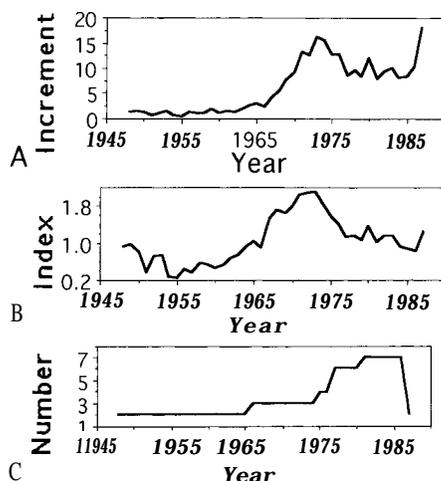

Fig. 9. For all discs belonging to spruce class four formed by cluster analysis, the average of cross-sectional area increment and ring index are plotted against year. Area increment is in cm^2 and is plotted in (A). Ring index is plotted in (B). In (C), the number of discs is plotted against year.

indices. Although there is year-to-year fluctuation in increment and indices, there is no evidence of a recent decline in growth.

The discs from spruce class four represent trees that responded to release from competition, but generally after relatively few years of suppression. The c parameter was positive for this group as well, indicating an increasing growth pattern. The graph of raw area increment and ring index (Fig. 9) are sensitive to the addition of more discs to the average; there are few discs in this group and only three before 1974.

Only four discs were included in spruce class five (Fig. 10). The discs represent trees that were released from suppression. Although the ring index decreased from 1965 onward, this was due to a poor fit of Eq. (1) to the data. The raw area increment remained level. Most models used in dendrochronology fit poorly when trees have been released. A pattern in the residuals will be evident, but it may not be clear that a poor fit in the most recent years is caused by an inadequacy in the model rather than atypical recent growth.

Although there is no compelling evidence for a growth decline, some of the discs did have declining area growth, mainly in classes one and two. We identified a declining trend when the oldest prediction
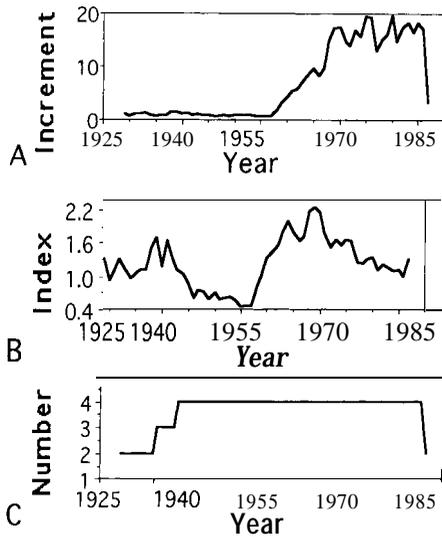
Fig. 10. For all discs belonging to spruce class five formed by cluster analysis, the average of cross-sectional area increment and ring index are plotted against year. Area increment is in cm' and is plotted in (A). Ring index is plotted in (B). In (C), the number of discs is plotted against year.

was more than 20% lower than the maximum prediction for that disc. This is conservative since many non-declining raw growth series produced a fitted equation that did decline. This was caused by the inadequacy of model 1 to fit released trees. Of the discs identified by this criterion, only 12 of them exhibited decreasing growth. The 12 discs came from two plots. Eleven of the discs were from trees which were smaller in diameter and height than other trees on the plot. Thus, the decline in growth was most likely to be due to these trees being out-competed by the larger trees. The remaining observation of decrease occurred in a disc from a tree which had lost its leader about 25 years before harvest. Thus, there is no evidence of any inexplicable recent cross-sectional area growth decrease in any disc measured in this study.

3.2. Height growth

Goelz et al. (1987) and Goelz and Burk (1998) have reasoned that height growth of dominant and co-dominant trees is a more suitable variable to study when considering relationships between long-term tree growth trends and anthropogenic factors, as height growth is less sensitive to many factors that

affect cross-sectional tree growth, primarily stand density and stand dynamics.

The Schumacher height growth Equation 2 and the simple difference form of Richards' function [3] fit poorly. The expanded second-order difference form of Richards' function [4] fit better, yet the model still seemed misspecified as several data points had a very large influence; a few trees seemed to grow in a different manner than other trees in the data set. Misspecification occurred because all spruce trees were included in the data set regardless of whether they were dominant trees or saplings in the understory, or whether they had ever lost a leader. All trees that were less than 8 m tall at 50 years of age, were deleted. Trees that were less than 50 years of age but were 8 m tall, or were expected to become 8 m tall before they reached 50 years, were included in the data set. Finally, the remaining trees were screened and those exhibiting a marked discontinuity were deleted from the data set as they were likely to have encountered some top damage in the past. These trees were deleted because they represented a different population (understory saplings or top-damaged trees).

Eq. (4) fit the remaining height growth data fairly well. The residuals from non-linear regression are plotted against year in Fig. 11. If there is no long-term growth trend, the residual plot versus year should show no pattern as the regression model adjusts for age. The data have been smoothed by a non-parametric smoother algorithm called LOWESS (Cleve-
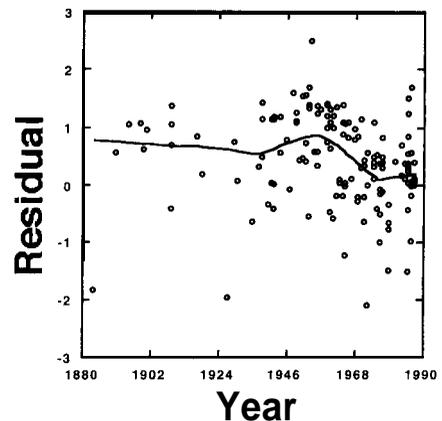

Fig. 11. Residuals from fitting Eq. (5) to the height growth data are plotted against year. The line was produced by the LOWESS algorithm.

land, 1979). A trend of decreasing residuals may be observed from 1950 to 1970.

If height growth is a more sensitive index of long-term growth trends, then this result may indicate that some factor has decreased growth within the last 37 years although cross-sectional area data did not show the trend. However, we feel that this conclusion might be premature for the following reasons. The height growth data set was small and some of the data may be from suppressed or damaged trees regardless of our screening. The trend is very linear which suggests that some problem lies in the model, although it fit fairly well. Finally, large negative residuals are scattered across the range of years rather than showing any great clustering at the most recent years. We suggest that a larger, cleaner data set is necessary to arrive at any firm conclusion regarding long-term trends in height growth.

3.3. Contrasts with other studies

Recent declines in red spruce diameter growth and associated increases in mortality have been observed at high elevation sites in both the northern and southern Appalachians (Bruck and Robarge, 1984; Johnson et al., 1984; McLaughlin, 1985; McLaughlin et al., 1987; Cook and Zedaker, 1992; Peart et al., 1992 among others). The results from the northern Appalachians are much more compelling in that the growth decline appears abrupt and sustained. Balsam wooly adelgid has killed Fraser fir on Mt. Mitchell, one of our study sites (Witter and Ragenovich, 1986) and red spruce is known to be sensitive to exposure (Harrington, 1986). Thus red spruce may decrease in growth in response to increased exposure caused by adelgid-killed fir.

McLaughlin et al. (1987) suggest that a recent regional growth decline has occurred in red spruce throughout the eastern United States, including sites in the southern Appalachians. Adams et al. (1985), Cook (1988), and Ord and Derr (1988) have also observed a recent decline in the radial growth of red spruce in the southern Appalachians. Although recent growth declines may have occurred, periodic growth declines may be a normal part of natural red spruce stand dynamics (Van Deusen, 1990; Reams and Peterson, 1992). Cook and Zedaker (1992) believe that while the growth decline observed in the northern Appalachian

spruce stands is probably unprecedented, the degree of decline in southern Appalachian spruce stands has numerous historical precedents. LeBlanc et al. (1992) indicate that the current prevalence of trees with declining growth is within the historical range for the Great Smoky Mountains red spruce population. Reams et al. (1993) indicate that the radial growth of red spruce on Clingman's Dome, North Carolina have increased and decreased at least nine times over the last 200 years, with no evidence of constant radial growth for extended periods of time. The results of these studies indicate that at least some southern Appalachian red spruce trees have exhibited a recent decline in radial growth; this decline may represent natural disturbance and stand dynamics patterns.

The conclusions of McLaughlin et al. (1987) are largely based on intervention analysis (Box and Tiao, 1975) and predicted ring indices using a climate model fit to data from the early part of the ring width series. Intervention analysis may give largely biased results when one draws inferences from the number of negative interventions occurring for a given period. As trees that tend to have negative interventions also tend to be trees that will die, a sample of currently living trees will be a censored sample of past growth. Inferences based on classical dendrochronology are sensitive to this type of censoring (Zedaker et al., 1987; Lucier et al., 1989); intervention analysis would be more sensitive as it focuses on discrete events although classical dendrochronology at least allows greater resolution of trends. Extrapolating a climate model is dangerous. This presumes that climate variables are included in a true model rather than a simple construct that describes past data and presumes that ontogeny does not affect growth or affect the relationship between climate and growth. Eriksson (1989) has shown that current dendrochronological techniques are biased in the estimation of climatic effects.

The common finding in published results regarding radial growth of red spruce is that a decline in growth has occurred in the recent past, although the decline may have ended (Reams et al., 1993). This contrasts strongly with our data. We could find no tree exhibiting decline in cross-sectional area growth except for a few trees that were in subordinate crown positions or one that had broken its top in the past. The difference in the data reflects a difference in data collection. Our data represents relatively young trees, largely from

even-aged stands or at least even-aged patches. To varying degrees, the other studies concentrated on older trees in stands of varying stand history. As no growth decline was found in our data, but was observed in other data and the data sources differed with regard to stage of stand development, stand development could be implicated in growth decline observed by other researchers.

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