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# Dendroclimatological analysis of major forest species of the central Appalachians

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**Abstract**

A dendroclimatological study was carried out in the 80-year-old Fernow Experimental Forest of the U.S. Forest Service near Parsons, West Virginia (39°20′N, 79°40′W). The relationship between radial and basal area increments and corresponding monthly, seasonal, and yearly mean air temperature and precipitation were obtained over 53 years for four species: black cherry (*Prunus serotina* Ehrh.), northern red oak (*Quercus rubra* L.), white ash (*Fraxinus americana* L.), and yellow poplar (*Liriodendron tulipifera* L.). These species show positive growth responses to rainfall of previous summer, autumn, and current summer. They show significantly inverse correlation to air temperature of the current growing season. The indices of radial increment show a close correlation to those of basal area increment. However, in our analyses, basal area increment indices are more sensitive to climatic variations than radial growth indices. © 1997 Elsevier Science B.V.

## 1. Introduction

Forest regions are broadly defined by climatological values of air temperature and precipitation (Rumney, 1968). These parameters are among the principal factors affecting forest growth and their seasonal and year-to-year variations affect the rate of biomass production. The relationship between climate and growth of trees, expressed by radial or basal area increments, has been studied for many years (Fritts, 1976). Such relationships, based on data from the past, can be utilized in making predictions of the possible effect of global warming on forests.

This issue is of special interest in West Virginia where about 78% of the land area is covered with forests. Dendroclimatological research has been carried out in the region since the 1950s. Tryon and Myers (1952), Tryon et al. (1957), Tryon and True (1958) used tree-ring data in the study of forest growth in West Virginia. Dean (1968) and Lanasa (1971) reported on the responses of radial growth to silvicultural treatments in the Appalachian mountains, and Schwegler (1983) estimated precipitation in the past in north-central West Virginia using a dendrochronological approach. Despite the progress achieved by these studies, dendroclimatological research in the central Appalachians is far from complete. To a great degree, this is due to the complicated relationship between climate and growth of trees in these mesic closed-crowned forests as stated by Phipps (1982); this relationship is not always effectively revealed by conventional dendroclimato-

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logical methods, such as linear correlation. The purpose of this study was (1) to obtain tree-ring data for selected Appalachian hardwood species, and (2) to define the growth responses of these species to variations in precipitation and temperature using improved statistical approaches.

## 2. Study site

The area under study is the control watershed, Watershed 4 (WS4) in the Fernow Experimental Forest, near Parsons, West Virginia (39°20′N, 79°40′W, Fig. 1). The watershed has an area of 38.7 ha and an east–south–east orientation. The average slope inclination is 14° and the average elevation is 804 m, with a maximum of 896 m on the northern part of the ridge line and a minimum of 739 m at the bottom of the watershed. The predominant soil is Calvin silt loam and the average soil depth is 0.8 m (Patric, 1973). The major forest types in this watershed are upland oaks and cove hardwoods. Among 35 species found in the watershed, the most prevalent, based on the decreasing biomass, are northern red oak (*Quercus rubra* L.), sugar maple (*Acer saccharum* Marsh.), black cherry (*Prunus serotina* Ehrh.), red maple (*Acer rubrum* L.), chestnut oak (*Quercus prinus* L.), yellow poplar (*Liriodendron tulipifera* L.), American beech (*Fagus grandifolia* Ehrh.), and white ash (*Fraxinus americana* L.). The average air-dry above ground biomass is 320.3 Mt/ha (Tajchman et al., 1995).

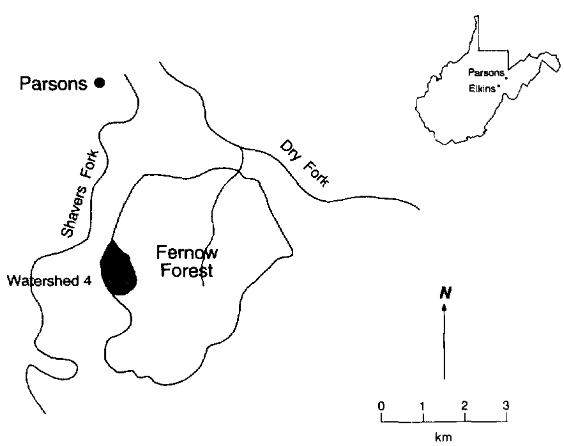


Fig. 1. Fernow Experimental Forest and Watershed 4 (WS4)

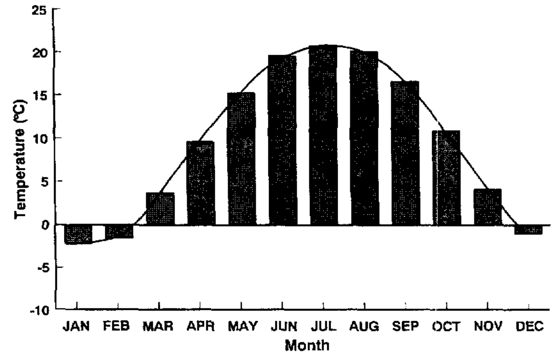


Fig. 2. Yearly course of monthly mean temperature (1900–1992)

The growing season in the study area is approximately from May through September, and the average length of the frost free season is 145 days. Leaves emerge in late April, they are fully developed by the beginning of June, and begin to fall in early October. The average yearly air temperature is 9.2°C, with a minimum of 7.0°C (in 1958) and a maximum of 11.3°C (in 1921). Fig. 2 shows the average monthly temperatures for the period 1900–1992. The average yearly precipitation of the watershed for the period 1900–1992 is 143 cm. The averages of monthly precipitation are seen in Fig. 3. The maximum average monthly precipitation is 13.91 cm, observed in June, and the minimum value is 9.15 cm in October. The greatest standard deviation of monthly precipitation (5.75 cm) is in August and the smallest (3.84 cm) is in April.

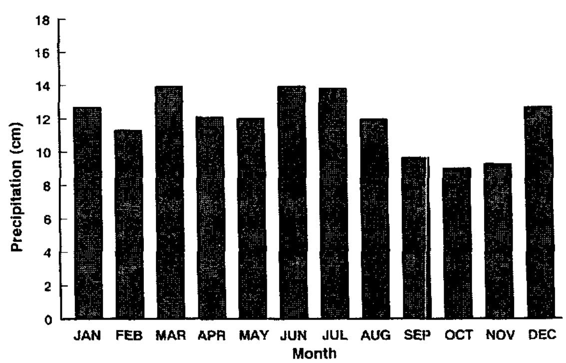


Fig. 3. Yearly course of monthly precipitation (1900–1992)

The climatological data used in this study were monthly sums of precipitation ($P$) and mean monthly air temperature ($T$) for the period 1900–1992. Observations of $P$ and $T$ at WS4 have been taken from 1951. Using linear regression, monthly $P$ and $T$ at WS4 were expressed as functions of these same parameters from climate stations at Parsons, about 3 km north of WS4, and at Elkins, about 24 km southwest of WS4. Missing $P$ and $T$ data for WS4 (1900–1950) were predicted using these regression models. $R^2$ values for $P$ ranged from 0.64 to 0.97, and those for $T$ ranged from 0.39 to 0.95. All regression models were significant at the 0.01 level.

During the winter of 1992–93, a heavy snow storm passed through the study area and many trees were uprooted. In the spring of 1993, 78 disks were collected from fallen trees as follows: black cherry (BC, 31 disks), northern red oak (RO, 16 disks), white ash (WA, 7 disks), and yellow poplar (YP, 24 disks). Most of those disks were cut at breast height (approx. 1.3 m). Disks were dried and specimens 1 cm wide and 0.5 cm thick were cut along four to six radial lines, depending upon the disk-eccentricity. A digital readout system (Acu Rite) was used to measure annual ring widths. A microscope attached to the system magnified specimen images so that annual rings' boundaries were identified to the nearest 0.01 mm.

Based on the visual observation, most of the yearly rings were not circular. To obtain the areas encompassed within rings, regression formulae were developed for each disk as follows: The areas encompassed within selected rings, $t$ intervals of several years of growth, were determined by planimeter. After that, the method of least squares was applied to express the area in terms of the average radius in the form of the polynomial and exponential functions (Pan, 1995). The following formula yielded the highest accuracy:

$$A_t = a \times R_t^b \quad (1)$$

where $A_t$ is the area encompassed in the ring of year $t$, and $R_t$ is the average radius of the ring of year $t$. The parameters $a$ and $b$ were determined using non-linear least squares. The yearly basal area increments ($\mathrm{BAI}_t$) were calculated as

$$\mathrm{BAI}_t = a\left(R_t^b - R_{t-1}^b\right) \quad (2)$$

## 3. Dendrological and dendroclimatological analysis

### 3.1. Tree-ring indices

Generally, tree-ring chronology is a time series incorporating and compounding different kinds of signals. According to Graybill (1982), any individual tree-ring specimen can be expressed as:

$$\mathrm{RI}_t = C + B + S + E \quad (3)$$

where $\mathrm{RI}_t$ is the measured ring width for year $t$, $C$ is the macro climatic signal common to trees at a site, $B$ is the biological growth curve as a function of tree age, $S$ is the tree disturbance signal including fire, insect damage or other disturbance, and $E$ is a random growth signal. The primary purpose of standardization is to remove non-climatic signals in a series that may include either a biological growth trend $B$, tree disturbance signal $S$, or both. This is done by fitting an appropriate curve $Y_t$ to a ring width series $\mathrm{RI}_t$, and calculating a new time series, called ring width index $Z_t$, as follows

$$Z_t = \frac{\mathrm{RI}_t - Y_t}{Y_t} \quad (4)$$

Generally speaking, the standardization for the growth series of hardwood trees is more difficult than that of conifers (Fritts, 1976). For simplicity, only the most recent 53-year period (1940–1992) was considered for standardizing the growth series in this study. There were two reasons for this selection. First, almost all of the trees regenerated before the 1940s at the study site. Second, for most trees, rapid growth periods ended in 1940, and then the stand entered a relatively steady growth period.

Each tree-ring series was first statistically normalized to obtain a scaled growth series $x_t$ and the scaled ring series was then standardized according to the general procedure provided by Fritts (1976). All the calculations were carried out using the SAS model procedure (SAS Institute Inc., 1993).

First, an attempt was made to fit an exponential form:

$$Y_t = a\exp(-bt) + k \quad (5)$$

If the correlation coefficient of fitting was high enough (in this study, $R^2 \geq 0.4$) and both parameters

$a$ and $b$ in Eq. (5) were positive, the exponential function was utilized for a given series. If these adequacy criteria were not met, for instance, if $R^2$ was very low, or the parameter $a$ or $b$ was negative, a straight line or a polynomial function (Eq. (6)) was applied.

$$Y_t = a_0 + a_1 t + a_2 t^2 + \dots + a_m t^m \quad (6)$$

The polynomial function is versatile, and sometimes, it is the only way to fit a trend of tree-ring series.

The standardization procedure was carried out for both radial and basal area growth series. Examples of fitted curves are graphed in Fig. 4a–d and Fig. 5a–d. In these figures, ring series are represented by the dimensionless values of annual growth, $Y$ is the trend function and $t$ is year-1939.

Radial growth of most oaks and white ashes fits the negative exponential form. This characteristic is similar to that of many coniferous species and is good for dendroclimatological study. However, black cherry and yellow poplar vary irregularly in their radial growths. Thus, the exponential form is not suitable to fit their growth trends, and they can only be fitted by polynomial functions. The basal area curves are more complicated than the radial growth curves, and in most cases, the polynomial forms are the only option for fitting these curves.

After an appropriate trend function was ascertained, the trend was removed from the scaled series, and the ring index series of each tree was obtained using Eq. (4). Then, the mean radial increment index and the mean basal area increment index for each species were obtained by averaging the corresponding index series for all trees of this species. Fig. 6a–d and Fig. 7a–d show the mean radial increment index and the mean basal increment index for each

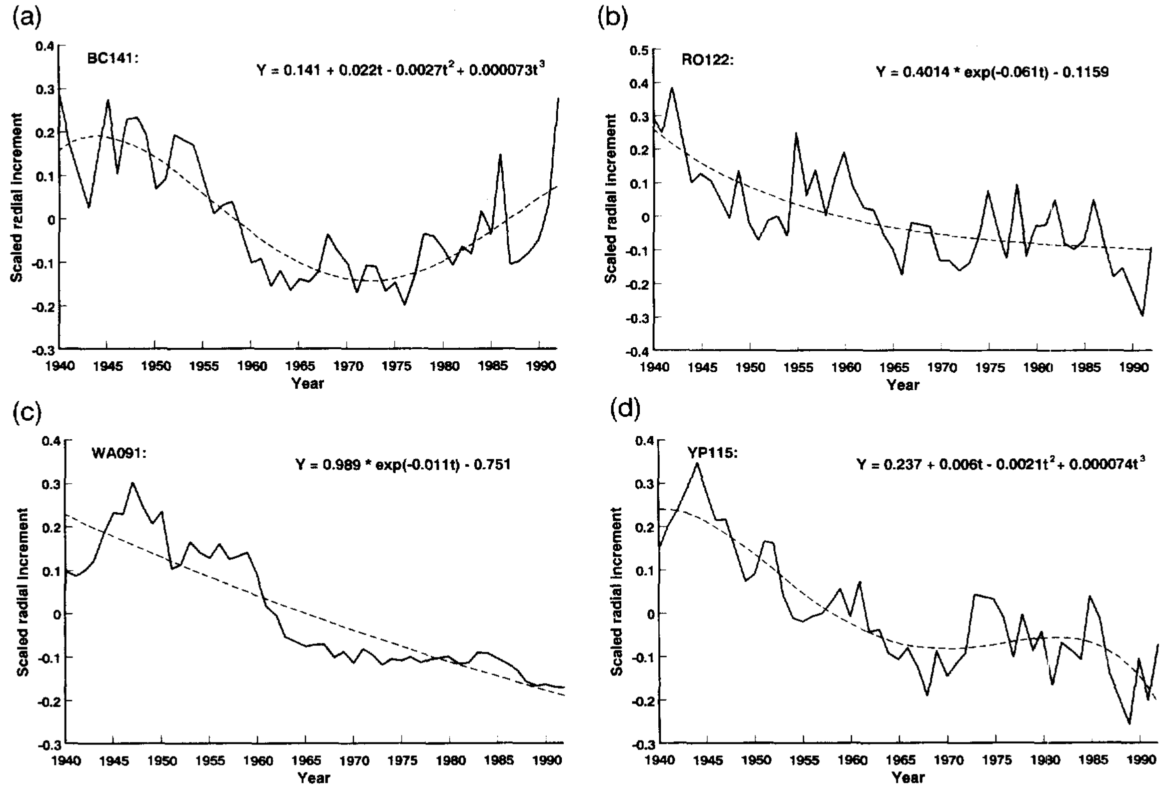


Fig. 4. (a) Trend function for radical increment of a black cherry, (b) Trend function for radical increment of a northern red oak, (c) Trend function for radical increment of a white ash, (d) Trend function for radical increment of a yellow poplar

species, respectively. The correlation coefficients between the radial increment index and the basal area increment index for each species are summarized in Table 1.

The correlations between the indices of radial increment and basal area increment are very high. Yellow poplar is among the species with the highest correlation (more than 0.9). The correlation coefficient of white ash is the lowest, but its $R^2$ is still more than 0.7. This fact suggests that the standardizing process has removed most of the non-climatic factors affecting tree growth, and both radial increment index and basal area increment index could provide similar results in the dendroclimatological analyses. Therefore, indices of basal area increment will only be used as dependent variables in the response function analysis.

### 3.2. Response function

In this study, the response function was calculated using principal component regression. A total of thirty climatic variables, which included monthly precipitation and monthly mean temperature from prior June to current August, were selected as predictors. The correlation matrix of both precipitation and temperature predictors, the eigenvectors of this matrix, and the uncorrelated principal components were computed using the SAS program (SAS Institute Inc., 1989). The first ten principal components were used as independent variables in the multiple regression, and the predictand was basal area index of each species. Finally, these partial regression coefficients of principal components were returned to the initial predictors, and the partial regression coefficient of

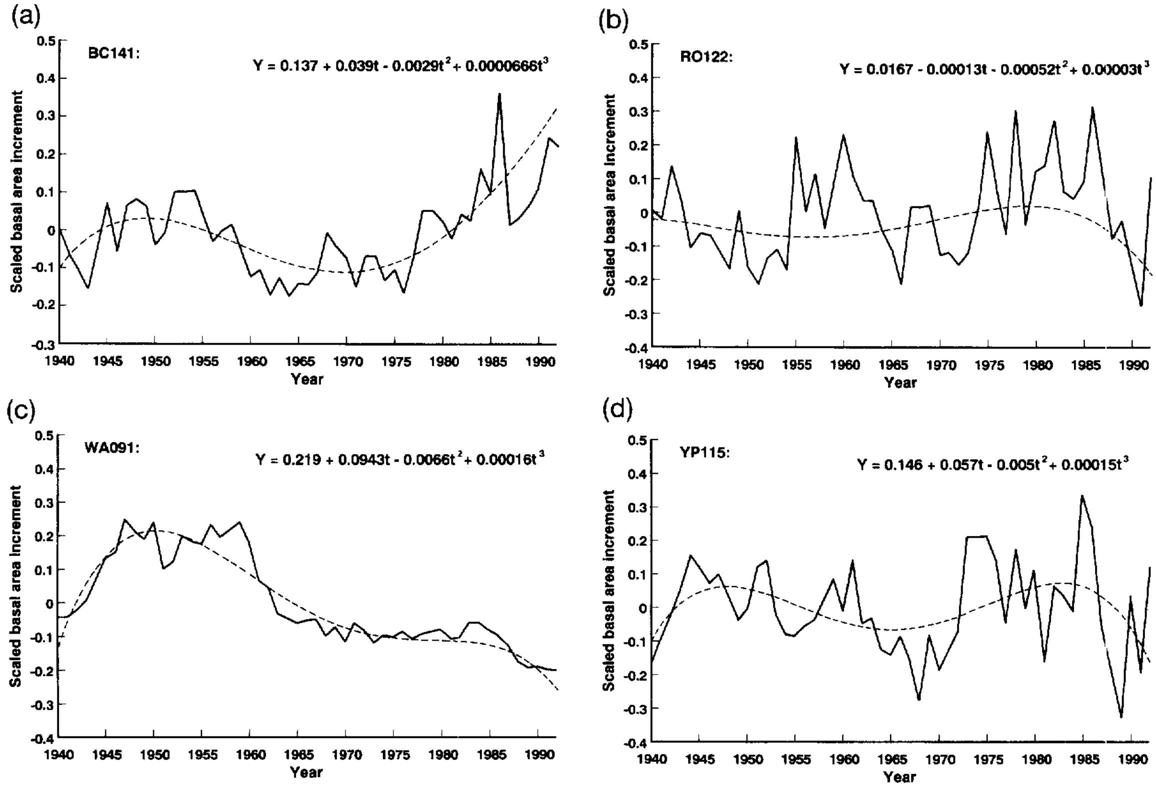


Fig. 5. (a) Trend function for basal area increment of a black cherry, (b) Trend function for basal area increment of a northern red oak, (c) Trend function for basal area increment of a white ash, (d) Trend function for basal area increment of a yellow poplar

each predictor represented the response of tree growth to the variation in precipitation and mean temperature for the particular month.

Graphs were drawn to depict these response functions (Fig. 8a–d). In these figures, response functions were expressed by dimensionless values. Following is a detailed interpretation of these analyses specific to each tree.

### 3.2.1. Black cherry

The response function of black cherry (Fig. 8a) shows a significantly positive correlation between growth and monthly rainfall of prior June, October, November and current April, July and August. Precipitation of prior September and the whole winter is inversely correlated with growth, while the rainfall of current May and June seems to be less important to early growth in the present year. Black cherry also shows a varying growth response to monthly mean temperature. The significantly negative temperature coefficients are for prior November and the current growing season, and a significantly positive coefficient for prior October and current February. These results imply that growth of black cherry is best in an area with cool growing seasons and abundant precipitation in summer and autumn.

### 3.2.2. Northern red oak

It is evident from the response function shown in Fig. 8b that precipitation is a dominant factor influencing the growth of northern red oak. The coefficients of precipitation are positive for most months except current April. In April, the coefficient of precipitation is negative and significant. The coefficients for summer and January temperature are significantly negative, and those for prior September, November and current May are significantly positive. It may be inferred from these temperature coef-

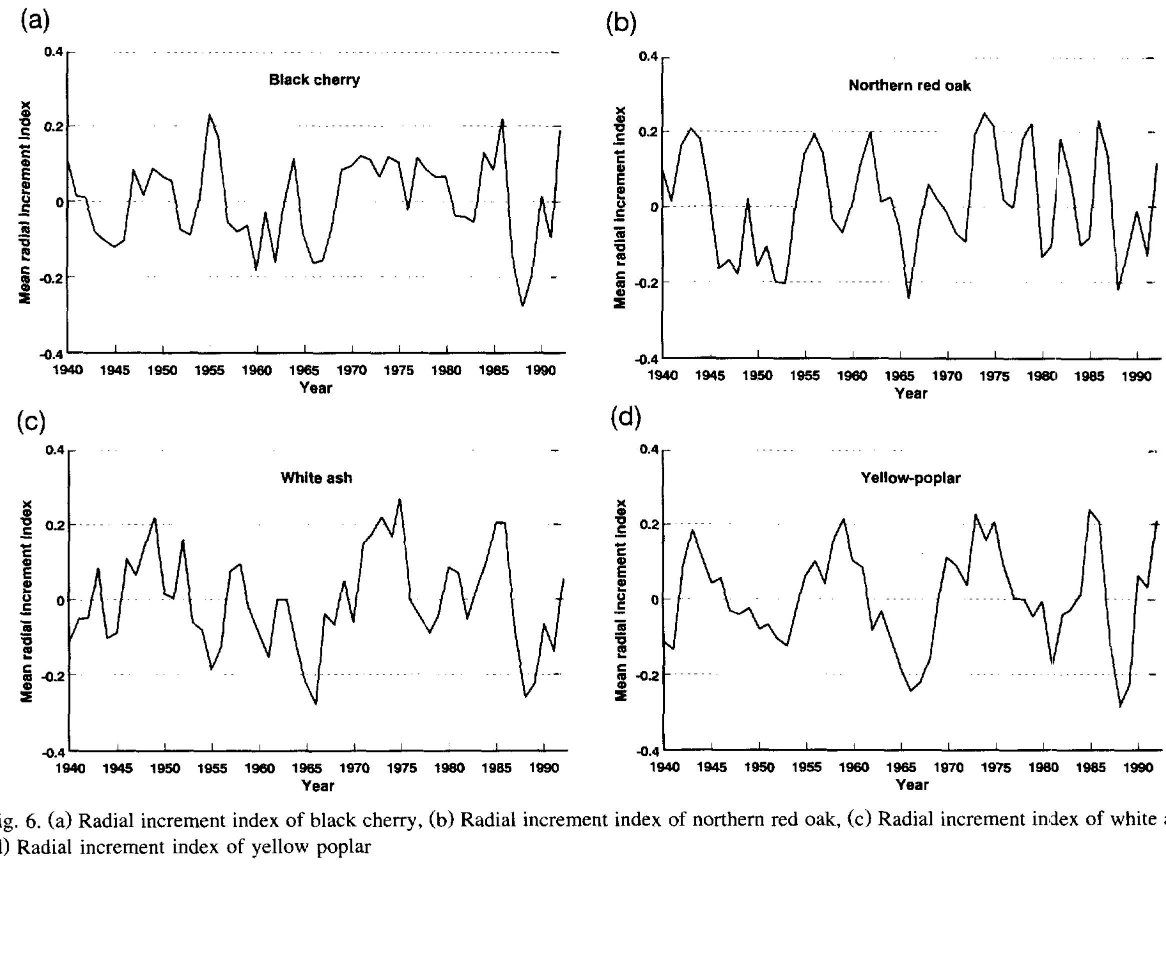


Fig. 6. (a) Radial increment index of black cherry, (b) Radial increment index of northern red oak, (c) Radial increment index of white ash, (d) Radial increment index of yellow poplar

ficients that northern red oak favors below-average temperature during summer and winter, but above-average temperature in Autumn and May. Especially, above-average temperature and moisture in May may promote rapid physiological activity of red oak early in the growing season.

### 3.2.3. White ash

Fluctuation in the response function of white ash to precipitation is similar to that of oaks, but its amplitude is larger than those of the oaks (Fig. 8c). Significantly positive coefficients of precipitation occur in prior June, October, November and in current June and July, while a significantly inverse correlation occurs for prior August and current March. Rainfall of the previous autumn is of special importance to this species. The response function of temperature for white ash presents a regular fluctuation. It is negative during the period from prior June to

Table 1
Values of $R^2$ between radial growth and basal area increment indices

| Species | BC | RO | WA | YP |
|---|---|---|---|---|
| $R^2$ | 0.8558 | 0.8924 | 0.7202 | 0.9439 |

All correlation coefficients in this table are significant at the 0.001 level.

September, then it is positive from October to current February, and, finally, it returns to a negative value from current March to August except for April. This characteristic suggests that below-average temperature during summer and above-average temperature during winter are beneficial to the growth of white ash.

### 3.2.4. Yellow poplar

The growth of yellow poplar is largely dependent on the variation in precipitation during the whole

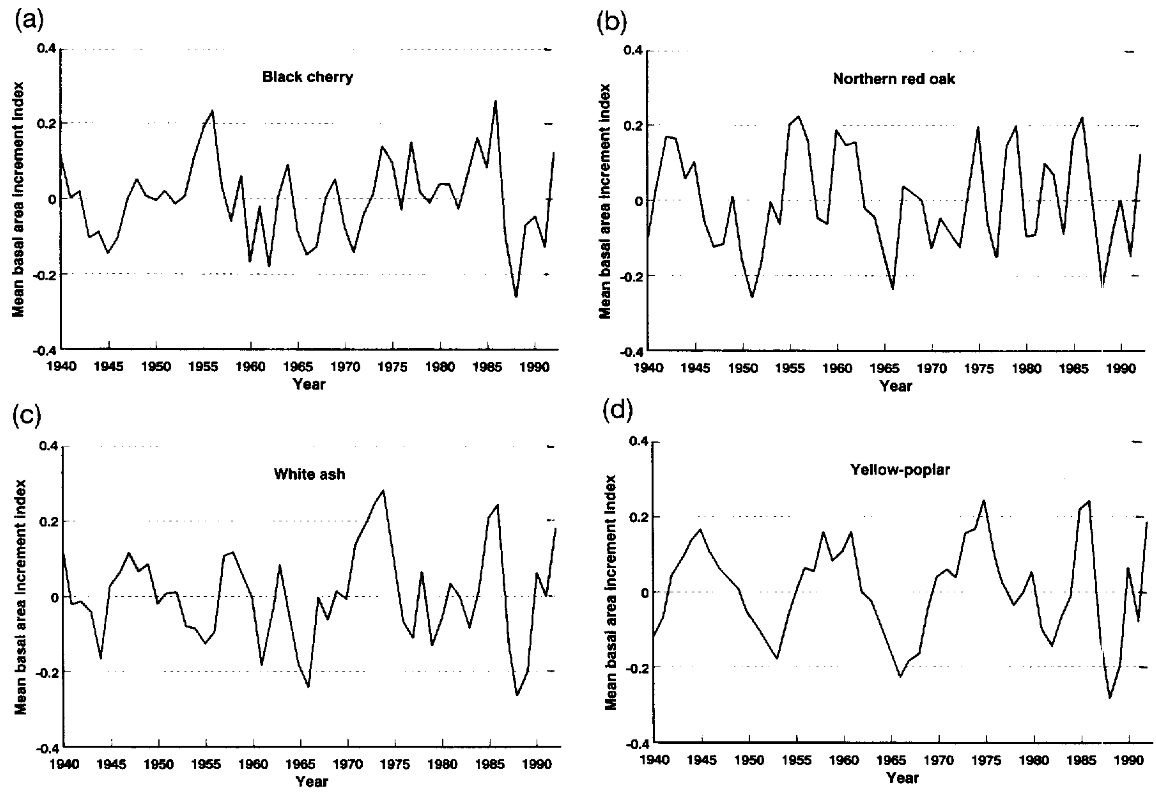


Fig. 7. (a) Basal area increment index of black cherry, (b) Basal area increment index of northern red oak, (c) Basal area increment index of white ash, (d) Basal area increment index of yellow poplar

year. From Fig. 8d, one can see that abundant precipitation in previous October and current July is the most important factor to the growth of yellow poplar. Negative response coefficients are found for August and September of the previous year and current spring, but they are insignificant. This result implies that yellow poplar favors a moist environment and therefore, it is more sensitive to variation in moisture

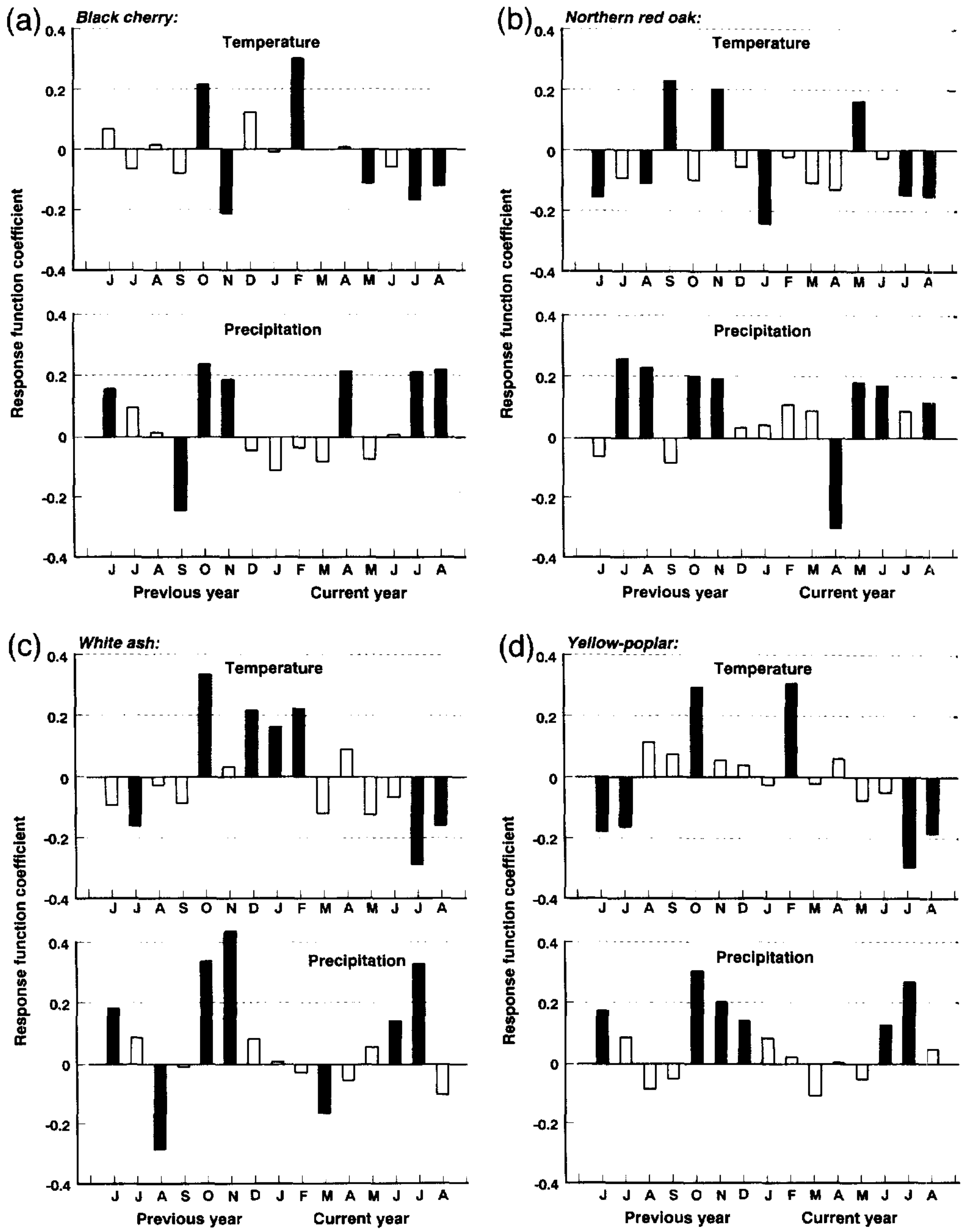


Fig. 8. (a) Response functions of black cherry, (b) Response functions of northern red oak, (c) Response functions of white ash, (d) Response functions of yellow poplar

Table 2
Predictands in the analyses

| Dependent variable | Description |
|---|---|
| RIBC | Radial increment index of black cherry |
| RIRO | Radial increment index of northern red oak |
| RIWA | Radial increment index of white ash |
| RIYP | Radial increment index of yellow poplar |
| BAIBC | Basal area increment index of black cherry |
| BAIRO | Basal area increment index of northern red oak |
| BAIWA | Basal area increment index of white ash |
| BAIYP | Basal area increment index of yellow poplar |

All predictands are dimensionless values.

than other species. The response of yellow poplar to temperature is similar to that of black cherry. It is inversely correlated with the growing season temperature, especially July. An above-average temperature during the non-growing season seems to be favorable to the growth of yellow poplar.

### 3.3. Regression analysis

The analyses of response functions of tree growth made it possible to develop regression models for growth of each species. The predictands of these regressions were the index series of both basal area increment and radial increment for each species (Table 2). All predictands are dimensionless. The predictors were variables grouped from monthly precipitation and monthly mean temperature (Table 3).

Stepwise regression (SAS Institute Inc., 1989) was used to develop these models. All predictor

Table 3
Predictors used in the analyses

| Independent variable | Description |
|---|---|
| PPJJ | Amount of precipitation from June to July of prior year |
| PPAS | Amount of precipitation from August to September of prior year |
| PPOD | Amount of precipitation from October to December of prior year |
| CPJAP | Amount of precipitation from January to April of current year |
| CPMJ | Amount of precipitation from May to June of current year |
| CPJAU | Amount of precipitation from July to August of current year |
| PTJA | Mean temperature from June to August of prior year |
| PTSO | Mean temperature from September to October of prior year |
| PTNM | Mean temperature from November of prior year to March of current year |
| CTAM | Mean temperature from April to May of current year |
| CTJA | Mean temperature from June to August of current year |

Precipitation (cm).
Temperature (°C).

Table 4
Regression analyses of tree growth indices

| Predictand name [a] | Intercept | Coefficient and variable [b] | $R^2$ | Probability $>\|F\|$ |
|---|---|---|---|---|
| RIBC | 0.6197 | +0.0037PPOD − 0.0394CTJA | 0.133 | 0.0284 |
| BAIBC | 0.8597 | +0.055PPJJ − 0.0545CTJA | 0.185 | 0.0062 |
| RIRO | 0.4779 | +0.0054PPJJ + 0.0057PPAS − 0.0420CTJA | 0.328 | 0.0014 |
| BAIRO | 0.4714 | +0.0058PPJJ + 0.0048PPAS + 0.0056PPOD − 0.0497CTJA | 0.332 | 0.0006 |
| RIWA | −0.3253 | +0.074PPOD + 0.0037CPMJ | 0.265 | 0.0004 |
| BAIWA | 0.3009 | +0.0039PPJJ + 0.0079PPOD + 0.0030CPMJ + 0.0197PTSO + 0.0212PTNM − 0.0541CTJA | 0.467 | 0.0001 |
| RIYP | 0.3510 | +0.0036PPJJ + 0.0073PPOD + 0.0319PTSO − 0.0574CTJA | 0.436 | 0.0001 |
| BAIYP | 0.4721 | +0.0039PPJJ + 0.0067PPOD + 0.0327PTSO − 0.0649CTJA | 0.469 | 0.0001 |

[a] See Table 2.
[b] See Table 3.

variables in these models were significant at the 0.15 level. The results are listed in Table 4.

Like the response function, these models reveal that mean temperature of the current summer (CTJA) is highly negatively correlated to the growth of nearly all the species. Precipitation of the current year is not as important for tree growth as the previous year's precipitation. The regression equation for basal area increment of yellow poplar shows the highest correlation ($R^2 = 0.469$). This demonstrates that yellow poplar is the most sensitive species to climate variation among the four species studied. White ash also shows a very high correlation to variation in precipitation and temperature. Another issue is, that for a specific species, although the predictors in the radial growth model and the basal area growth model are similar, the basal area growth model contains more climatic factors than the radial growth model. For instance, the equation for radial growth of white ash contains two factors (PPOD and CPMJ), while that for the basal area growth of white ash contains six predictors (PPJJ, PPOD, CPMJ, PTSO, PJNM and CTJA). One consequence is that the model for basal area growth is more significant ($R^2 = 0.467$) than that of radial growth ($R^2 = 0.265$).

It should be pointed out that, although these models provide a quantitative relationship between the ring indices and climatic parameters, they cannot be used as prediction equations to estimate future growth because these indices' series are not actual measurements of tree growth. These models can only be used as diagnostic equations.

## 4. Discussion

Results of the dendroclimatological analysis of this study are summarized below.

(1) All species show positive growth responses to rainfall of prior summer, autumn and current summer. By comparison, variation in precipitation in the previous year is more important to tree growth than variation in precipitation in the current year. This lag in response suggests that water deficit in the previous year directly or indirectly influences the number of leaf primordia that overwinter in buds and expand during the subsequent season. Hence, the amount of carbohydrates and hormonal growth regulators produced by leaves during the current year are affected by water deficit in the previous year (Kramer and Kozlowski, 1979)

(2) Air temperature is as important as precipitation in its influence on growth of most species. All species show a significantly inverse correlation to temperature in the current growing season. This occurs because extremely high temperature will lead to water stress and reduce apparent photosynthesis (Rosenberg et al., 1983). However, a relatively warm autumn and winter may favor the growth of some species the next year. Based on this phenomenon, one can postulate that warm weather in the late season may be responsible for an increase in photosynthesis, food accumulation or some other process which affects tree growth in the subsequent growing season (Fritts, 1976).

(3) After the standardizing process, the indices of radial increment show a close correlation with those of basal area increment. In most cases, these two indices provide similar information about the effect of climate on tree growth. However, in the model analyses, basal area increment indices are superior to radial growth indices. They are influenced more by climatic variables and, therefore, are more sensitive to climatic variations.

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