Tree-ring model interprets growth decline in natural stands of loblolly pine in the southeastern United States

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Annual ring widths and ring areas from 131 even-aged, natural, well-stocked stands of loblolly pine (*Pinus taeda* L.) in the Piedmont region were analyzed to reveal possible causes of a previously reported decline in radial growth. A linear aggregate model was used to separate independent factors that are known to contribute to radial growth variation in this species. Stand, site, and climatic conditions were reconstructed for each stand for the 36-year period 1949–1984 from previous inventories and from weather records at appropriately located stations. Within each of six 5-year age-classes, the model identified declines in both ring width and ring area associated with stand density, climate changes, and the passage of time. Regional climate first ameliorated this decline as pine stands passed from droughty conditions early in the 36-year period to a favorable climate during the middle of the period, and the decline accelerated later with the return of dry conditions toward the end of the period. The tree-ring model simulates a decline in radial increment in trees in natural pine stands between the ages of 20 and 45 years in the Piedmont which has averaged 1% per year since 1950. Part of the downward trend was attributed to increased competition, part to regional drought, and a considerable part to unidentified factors, possibly regional atmospheric deposition.

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La largeur ainsi que la surface des cernes annuels de 131 peuplements naturels et denses de Pin loblolly (*Pinus taeda* L.) d'âge uniforme situés dans la région de Piedmont ont été analysés dans le but de déceler les causes possibles du déclin manifeste de la croissance radiale. Un modèle linéaire global a été utilisé afin de dissocier les facteurs indépendants connus pour leur contribution aux variations de la croissance radiale pour cette essence. Les conditions climatiques, stationnelles et de peuplement ont été reconstituées pour chaque peuplement pour la période de 36 ans s'étendant de 1949 à 1984 à partir d'inventaires précédents et des données météorologiques provenant de stations bien localisées. Pour chacune des six classes d'âge de 5 ans, le modèle identifie le déclin dans la largeur et dans la surface des cernes associé à la densité de peuplement, aux changements climatiques et au passage du temps. Le climat régional a tout d'abord amélioré ce déclin alors que les peuplements de pin passaient de conditions xériques au début de la période de 36 ans à un climat favorable au milieu de la période, puis le déclin s'est accéléré avec le retour de conditions xériques en fin de période. Le modèle des cernes annuels simule que les pins en peuplements naturels âgés de 20 à 45 ans dans le Piedmont ont décliné en croissance radiale depuis 1950 d'une moyenne de 1% par année. Une partie de la tendance à la baisse a été attribuée à la compétition accrue, une partie à la sécheresse au niveau de la région et une partie considérable à des facteurs non identifiés, possiblement aux dépôts atmosphériques régionaux.

[Traduit par la revue]

Introduction

This paper reports a dendroecological investigation that helps to explain reductions in radial growth previously documented for the southern pines in the Piedmont region of the southeastern United States (Sheffield et al. 1985; Sheffield and Cost 1987). Diameter growth rates, measured outside bark at breast height on permanent survey plots at 10-year intervals, have dropped 30–50% over the past 30 years. The most severe growth reductions were found in trees between 15 and 25 cm dbh in young, even-aged natural stands of loblolly pine (*Pinus taeda* L.). Increment cores from a sample of these trees provided the ring measurements for the present study.

Dendroecology is a tool for evaluating variations in past and present forest environments (Fritts and Swetnam 1986). Tree-ring analysis of forest growth changes related to variations in environment over time requires two data components: (*i*) tree-ring chronologies validated for the period of concern, and (*ii*) measurements of environmental conditions as they vary over the period, in this case long-term weather records and field observations of stand and site conditions. Time-related region-wide growth declines are not readily detected in rings of young trees because the intrinsic age-dominated decrease in ring widths is too prominent. Standardization techniques that remove the age trend (Fritts 1976) obscure gradual growth changes that might be due to such exogenous factors as regional atmospheric deposition. The model used in this study permits age to be held constant while time varies (Zahner 1988).

The objective was to examine possible causes of the radial growth declines in natural stands of loblolly pine suggested by Sheffield and Cost (1987), in particular the impacts over the past four decades of changes in stand density and age, site conditions, drought and climate patterns, and regional atmospheric deposition. Lucier (1988) summarizes the key issues in analyzing these pine growth-rate changes.

Methods

Field plots

The Forest Inventory and Analysis (FIA) research work unit of the Southeastern Forest Experiment Station selected a 10% subset of their survey plots located throughout the natural range of loblolly pine in the Piedmont region of Georgia, South Carolina, and North Carolina (Fig. 1). FIA plots are random samples of forest land located on the landscape in a systematic fashion using photo grid points. Since the 1950s, trees have been measured at each of these sample plots at 10-year intervals. There are about 1340 such FIA plots in the natural loblolly pine type in the Piedmont survey units of the three states.

Criteria for selecting the subsample required that plots were located in undisturbed natural even-aged stands of the loblolly pine type between the ages of 25 and 80 years in 1984, with stand density within the normal range of basal areas and stocking levels, on typical Piedmont pine sites of site index between 18 and 28 m (at age 50 years). Each plot had been inventoried in three previous FIA surveys at 10-year intervals and was reinventoried in 1985. All stands selected for study were free of major disturbances over the survey period, and in 1985 there was no evidence of fire, severe insect or disease infestations, or thinnings or other harvest. Most stands included a few trees with fusiform infections, bark beetle mortality, ice and glaze breakage, and other typical ongoing impacts. Hardwoods were present as understory and midstory in all stands, and as a component of overstory in some stands. A total of 131 plots was selected for the dendroecological analysis.

Increment cores

Two increment cores were extracted at breast height from opposite sides of the bole on each of a minimum of five trees on each plot. Sample trees were selected subjectively as representative of healthy, undamaged dominant and codominant crown classes. The cores were prepared for measurement and cross-dated by visual inspection, and rings were measured to an accuracy of ± 0.01 mm with a digital micrometer, using standard techniques (Phipps 1985). Cross-dating for these short chronologies was aided by the occurrence of clearly defined signal years throughout all ring sequences (Fig. 2). Thus, all tree-ring measurements were absolutely dated.

Average ring width for each year of the respective tree-ring sequences for each plot was calculated from the ring-width measurements of individual cores. Average ring widths were plotted over calendar years for each plot (Fig. 2). Cores exhibiting anomalies due to excessive reaction wood beyond the juvenile stage were eliminated.

As clearly indicated by the examples in Fig. 2, ring-width sequences in these short-term, relatively young tree chronologies exhibit strong exponential decay curves with increasing age, following the initial period of juvenile wood formation.

Ring areas (i.e., annual increment of basal area inside bark) were calculated for each annual ring of each tree in all years for which ring-width measurements were available. Tree diameters were taken as the sum of the two radii sampled by the increment cores, measured from the pith to the edge of each annual ring.

Stand-age time series

Beginning with total stand age in 1984 (as determined from average ring counts at breast height plus 3 years), an age was assigned for each calendar year back to 1949 if the tree-ring chronology was at least 36 years, or as far back as the chronology extended for younger stands. A limited sample size for older stands excluded analysis for the years before 1949. Five-year age-classes were established by calendar year for each plot, beginning at age 18 years and ending at age 47. Each age-class includes 2 years before and 2 years after the midpoint of the class. Thus, age-class 20 consists of the 5-year calendar period from ages 18 through 22 for each plot. For example, a stand 39 years old in 1985, the year in which it was sampled, is represented by four age-classes: ages 20 in 1966, 25 in 1971, 30 in 1976, and 35 in 1981.

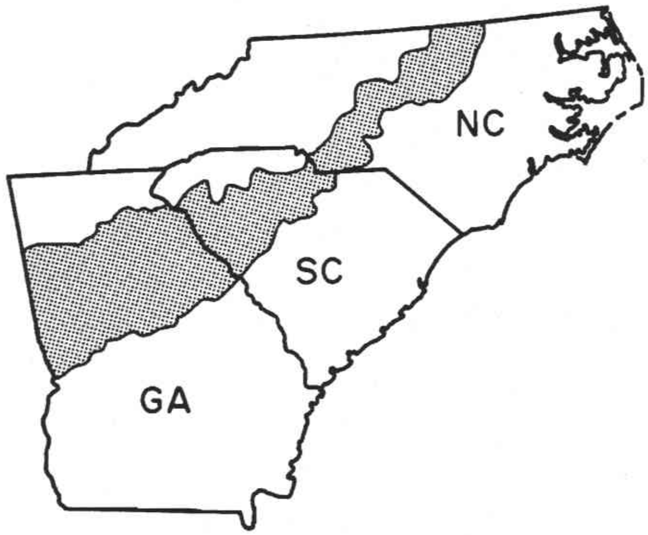

FIG. 1. Geographic location of the study area in the southeastern states of Georgia, North Carolina, and South Carolina (the natural range of loblolly pine in the Piedmont region).

The 131 plots exhibit stand age-classes well distributed across the period from 1945 through 1984 (Table 1). The 20-, 25-, 30-, and 35-year age-classes are well represented throughout all calendar years. The 40- and 45-year age-classes are less well represented in the early calendar years, a reflection of the current distribution of ages in the FIA sample. Most loblolly pine stands in the Piedmont are harvested by age 50; thus, the older stands sampled in 1985 represent a small population of surviving stands, whereas the younger stands sampled are from a large population.

Stand density

Basal areas and numbers of stems per hectare of both pine and hardwoods 2.5 cm dbh and larger had been measured on all plots at the 10-year FIA survey intervals before the 1985 inventory. These data, obtained separately for each plot, permitted the interpolation of stand density within survey cycles for each calendar year for which there were tree-ring measurements for that plot.

A stand density index (SDI), based on basal area multiplied by the number of stems, was assigned to each plot for each year for which that plot had a tree-ring measurement between 18 and 47 years old. Twelve stand density classes resulted from the numerical range of combinations of basal area and number of stems: from minimally stocked SDI class 1, with basal area less than 14 m^2/ha $\times$ 700 stems/ha, to maximally stocked SDI class 12, with basal area 40 m^2/ha $\times$ 2000 stems/ha. This index was based on the rationale that competition for pine growth from understory and midstory hardwoods is related to increasing numbers of all trees larger than 2.5 cm dbh. The 12 index classes are in direct proportion to the product of basal area and number of stems.

Climate

Fifty-four climatological data stations (National Oceanic and Atmospheric Administration 1986) were selected throughout the three-state Piedmont region as appropriately located to provide daily weather data for the 131 loblolly pine plots. Daily maximum and minimum temperatures and precipitation amounts were obtained from NOAA files for the period 1949–1984 for each of the 54 stations. Each plot was assigned to one or more of the weather stations best located geographically to represent the climate at that plot.

TABLE 1. Distribution of age-class observations by 10-year calendar year class for 131 Piedmont loblolly pine plots

	No. of observations				
Age-class	1945–1954	1955–1964	1965–1974	1975–1984	Total
20	11	27	36	15	89
25	10	17	44	16	87
30	8	12	27	36	83
35	2	12	17	43	74
40	1	9	12	26	48
45	0	2	11	16	29
Total	32	79	147	152	410

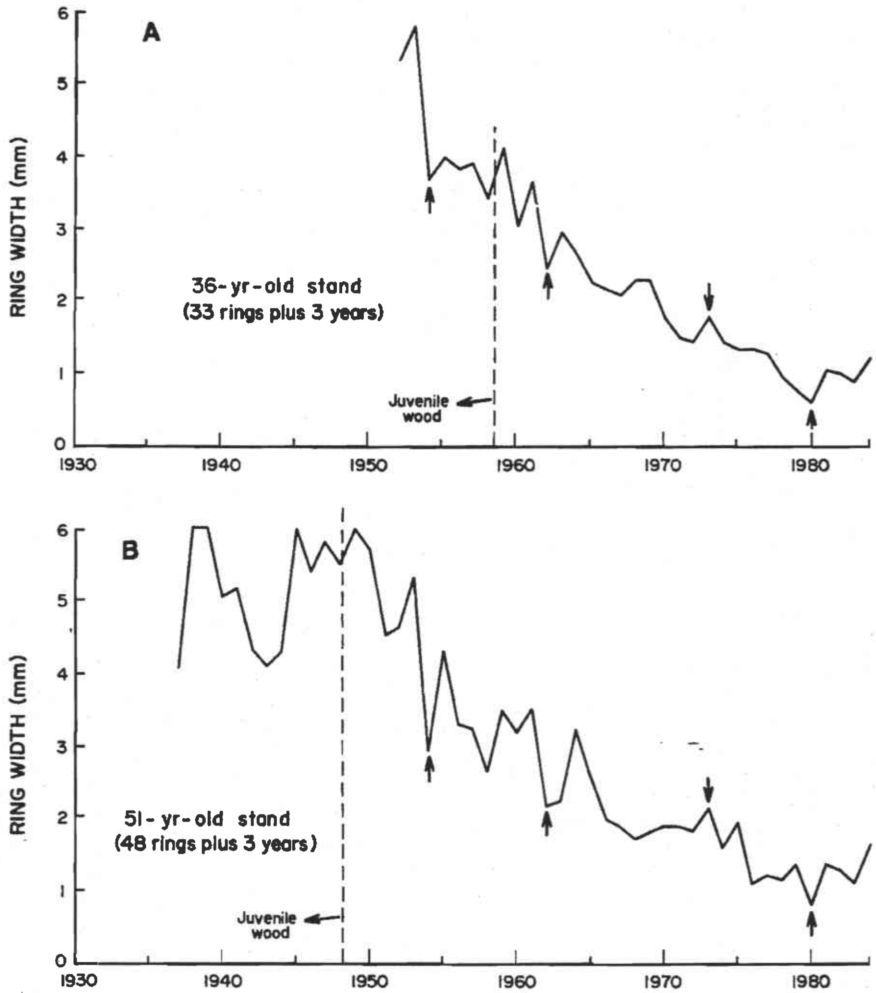

FIG. 2. Examples of tree-ring chronologies for two stands. Plotted lines connect average ring widths measured on all cores in each stand. (A) Ring widths used from 1967, when stand was 18 years old, to calculate 5-year age-classes, beginning at age 20 in 1969. (B) Ring widths used from 1952, when stand was 18 years old, to calculate 5-year age-classes, beginning at age 20 in 1954. Arrows indicate signal years used in cross-dating.

To establish the age-related decrease in ring widths, so prominent in these short-term chronologies (Fig. 2), it was necessary to reduce the large annual variation in ring widths due to current weather. Fritts' (1976) climate response functions were not used because the indexing procedure removes not only the age-related decrease but all trends related to the passage of time. In this study, it was necessary to account for both the annual impact of weather and the long-term trends of regional climate.

Two simulation models were developed to assess these two impacts of climate on the tree-ring sequences. The first model, FORDROUT (forest drought) (Zahner and Myers 1986), was used to calculate the annual variation in radial growth attributable to current weather and to the interaction of water deficits and site. The second model, DISP (drought index for southern pines) (Zahner and Grier 1989), was used to evaluate the multiple-year, lagged cumulative effect of regional climate on tree-ring growth trends.

The FORDROUT model consists of four parts, adapted from

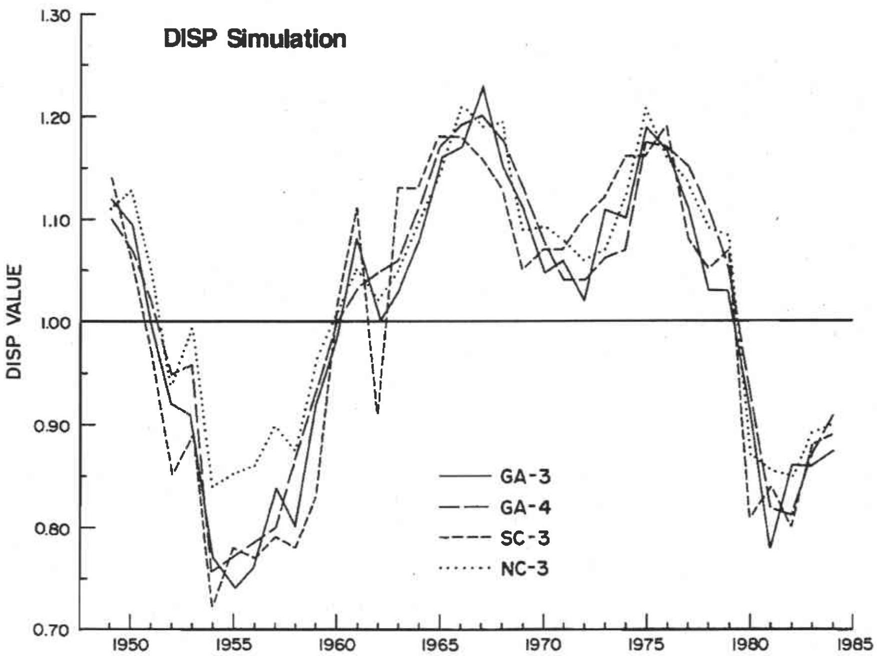

FIG. 3. Three-year preconditioned averages for DISP values calculated from 1949 through 1984 for four FIA survey units in the Piedmont region from west-central Georgia northeast across South Carolina to central North Carolina. Each DISP value represents the 3-year cumulative impacts on forest health of the Palmer Drought Severity Index relative to the long-term average condition for the survey unit. Values greater than 1.00 represent a favorable climate for radial growth and values less than 1.00 are unfavorable.

Zahner and Stage (1966): (1) simulation of the climatic water balance (Thornthwaite and Mather 1955) calculated from daily weather records; (2) simulated annual reconstructions of soil-moisture regimes for well-defined soil profiles and site conditions (Zahner 1966); (3) calculations of daily water deficits (Federer 1980) for each selected site; and (4) simulations of daily rates of tree growth throughout the growing season, reduced from or increased above the long-term average daily growth by the magnitude of the water deficit or lack of deficit (Zahner and Myers 1986). Daily growth is accumulated for each annual growing season and expressed as a proportion of long-term average annual growth.

The FORDROUT model was used to calculate adjustments to measured ring widths for the purpose of minimizing annual variation in growth due to water deficits and site. FORDROUT in effect adjusted each ring width upward to assumed mean growth during years of severe water deficits and downward during years of favorable weather. The model also adjusted for site quality by simulating growth responses to weather and soil interactions for the specific site conditions on each plot. The site by site adjustment is proportional to that reported by Brender and Clutter (1970) for natural stands of loblolly pine in the Georgia Piedmont.

The DISP simulation uses monthly values of the Palmer Drought Severity Index (Palmer 1965) from NOAA files to calculate an index of annual radial growth relative to long-term average radial growth, based on the antecedent accumulated effect of climate over a geographic region of uniform climate. It is not site specific. The model accounts for both the timing and intensity of current and antecedent wet and dry periods in relation to the long-term average condition. The lagged preconditioning effect of climate on current growth is simulated by giving more weight to monthly values of the Palmer index for 1 year before the current year than to values for 2 years before.

Preconditioned DISP values were calculated for 10 separate NOAA climatological divisions within the three-state Piedmont region for the period 1949–1984. Each plot, within its appropriate climatic area, was assigned 2-year preconditioning indices combined with the current index for each calendar year. The combined indices were in turn averaged for each of the corresponding 5-year age-classes for that plot. Long-term trends of regional climate are evident when DISP values are averaged over all NOAA climatological divisions in each FIA survey unit (Fig. 3).

Soil–site relationships

Piedmont Ultisols and Alfisols are derived from deeply weathered residual granite, schist, and gneiss, generally with 75–150 cm to saprolite or weathered bedrock. Piedmont sites supporting natural stands of loblolly pine are drought prone because of the hilly terrain, past land abuse, and potentially restrictive rooting depth. Pine stands have seeded naturally onto sites that have been periodically disturbed by European man for over 200 years. The 131 stands were all located on sites that indicated prior agricultural use, exhibiting from mild to severe erosion of the original surface soil.

From field descriptions and measurements of the soil profile, soil series, topography, land-use history, and severity of old field erosion, and measured site index (SI) for loblolly pine, each plot was assigned site productivity and drought susceptibility ratings. Site quality was based on the following criteria (SI base age 50 years):

(*i*) Below-average sites (SI below 21 m). Upper slopes, surface soil severely eroded to less than 15 cm residual thickness, clay subsoil, very plastic to plastic, poorly aerated below 30 cm, limited effective rooting depth, total available water less than 12 cm.

(*ii*) Average sites (SI 21–24 m). Broad ridges or midslopes, surface soil moderately eroded to between 15 and 30 cm residual thickness, moderately effective rooting depth, total available water 12–15 cm.

(*iii*) Above-average sites (SI above 24 m). Broad ridges or lower slopes, surface soil slightly eroded with more than 30 cm residual thickness, clay to clay loam subsoil slightly plastic to friable, well aerated to 100 cm, good effective rooting depth, total available water over 15 cm.

These soil and site characteristics were used to determine the soil water depletion and accretion regimes for each plot as calculated by part 2 of the FORDROUT simulation.

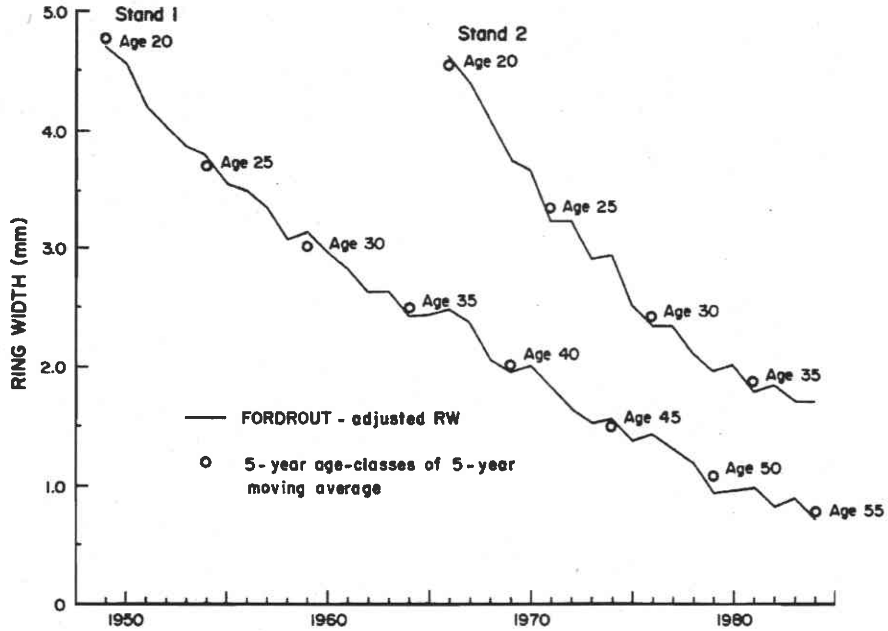

FIG. 4. FORDROUT-adjusted ring widths (RW) for two stands. Plotted points are average ring widths for 5-year age-classes of 5-year moving averages of the FORDROUT-adjusted ring widths. The model uses age-classes 20 through 45.

The passage of time

Time is measured in this study by calendar year. It is assumed that the potential impacts of regional atmospheric deposition on radial growth of Piedmont loblolly pine are exogenous factors whose effects accumulate over time. Tree-ring "declines" that cannot be associated with natural exogenous factors affecting all stands in a region, and are correlated with the passage of time, could be associated with atmospheric deposition. This assumption must be based on correlations, not controlled experiments, and the results cannot be taken as proof of a relationship. However, the analysis provides a means of testing the effects of climatic conditions and stand competition in pine stands of equal ages as opposed to a hypothesized effect of atmospheric deposition acting over time.

Tree-ring model

The model developed for this study is an adaptation of Graybill's (1982), Cook's (1986), and Zahner's (1988) linear aggregate models for the potential components of tree-ring variation, the last model suggesting in particular a method for examining growth declines. The dependent variable RW_t, representing a mean ring-width measurement for the middle year of a 5-year age-class accurately dated to calendar year t, is modeled as the aggregate of seven basic components:

1. The age-related growth trend in year t which is shared by all dominant and codominant loblolly pine trees in a given stand. This trend is the ring-width decay curve associated with increasing stand age that arises from the geometrical constraint of adding tree rings to stems of increasing diameter. This trend was modeled with a reciprocal function for the mean age of the 5-year age-classes.
2. The climatically related growth variations common to a given stand of trees in year t, including current weather, lagged preconditioning climate, and the interaction of climate with specific site conditions. The site-specific rainfall and temperature patterns of each growing season were modeled with the FORDROUT simulation, and the regional cumulative climate was modeled with the DISP simulation.
3. The growth pulses within a given stand, originating from changes in competition, stand structure, and stocking levels acting on sampled trees in year t. This component was modeled by the stand density index.
4. The disturbance pulses in year t originating from forces outside a given stand, such as harvesting, ice storms, insects, or diseases. This component does not enter the model because all stands exhibiting abnormal disturbance were eliminated either during the original FIA field selection of plots or later by the examination of increment cores.
5. The effect of site, reflecting the edaphic characteristics of soil, topography, and geology that regulate productivity for a given stand, which is constant all years for that stand. The FORDROUT model adjusted ring widths for site variation through the interaction of site with climate. In addition, measured site index was used as an independent variable for each plot.
6. The calendar year, t, a measure of the independent effect on ring width of the passage of time, unrelated to the age of the stand. For a population of stands, a change in ring widths related independently to this component within a given age-class represents an increase or decrease in radial growth over time for the population (Zahner 1988).
7. The random error in ring width in year t due to unmeasured growth-influencing factors such as microsite, genetic composition, variation in radius around the circumference of the bole, and mismeasured site, climate, tree, or stand variables.

Simulation for ring-width time series

The model described in the previous section describes four different components that are known to contribute to radial growth variance in undisturbed even-aged stands of loblolly pine: age, climate, stand density, and site. A suspected growth change associated with the passage of time, component 6, can be identified only after analysis has quantified the effects of the four known components (Zahner 1988). Multiple regression analysis was used in the linear aggregate model as an appropriate technique to fit the measured field and laboratory data to a time trend (Draper and Smith 1966; Zahner and Stage 1966) and to test the significance of each component.

The age-associated trend toward decreasing ring widths was first enhanced by calculating annual FORDROUT-adjusted ring widths as 5-year moving averages for each plot (Fig. 4). This simulation removed the large year to year variation associated with growing-season soil water deficits which is so evident in Fig. 2. These 5-year moving averages were collated by 5-year age-class, beginning with age 20 years (Fig. 4). The 36-year period from 1949 to 1984 yielded

TABLE 2. Statistics for ring-width regression equation (eq. 1) and ring-area regression equation (eq. 2); variables are listed in the order of their contribution to sequential R^2 values

(A) Ring width[a]

Variable	Mean	Coefficient	SE	P that $b = 0$	Sequential R^2
1/AGE	0.0357	30.42	±2.99	<0.001	0.320
SDI	5.05	−0.111	±0.010	<0.001	0.498
YR	70.8	−0.0378	±0.0035	<0.001	0.608
C	1.03	0.649	±0.196	0.001	0.638

[a]Based on 410 observations, $b_0 = 4.193$.

(B) Ring area[b]

Variable	Mean	Coefficient	SE	P that $b = 0$	Sequential R^2
DIAM	19.86	0.833	±0.023	<0.001	0.399
AGE	29.4	−1.298	±0.031	<0.001	0.466
SDI	7.88	−0.331	±0.025	<0.001	0.544
YR	71.3	−0.142	±0.015	<0.001	0.586
C	1.02	2.88	±0.77	0.005	0.608

[b]Based on 1178 observations, $b_0 = 13.95$.

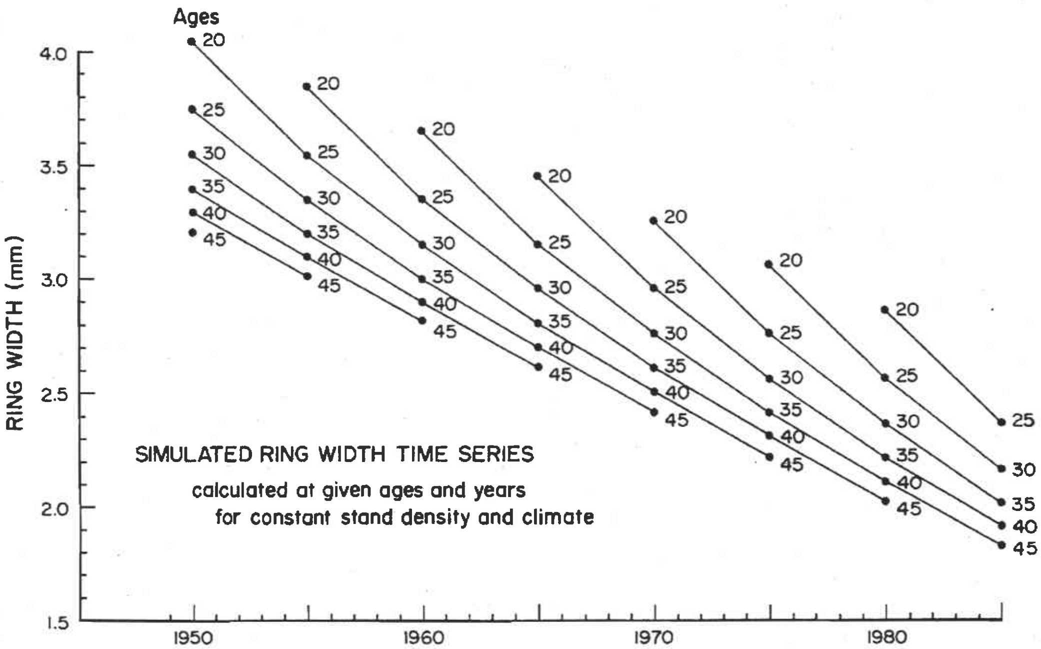

FIG. 5. Ring-width time series calculated using eq. 1 for stands 20 years old in 1950, 1955, 1960, 1965, 1970, 1975, and 1980, and for stands 25, 30, 35, 40, and 45 years old in 1950. Stand density index is held constant at long-term mean value for each age-class, and C is held constant at long-term normal value.

410 such ring width versus age-class observations for the 131 plots (Table 1).

A multiple regression model was used to simulate tree-ring time series to detect possible growth changes within age-classes (Zahner 1988). Observations from all six age-classes were pooled to calculate the coefficients in the following model:

$$\mathrm{RW} = b_0 + b_1(1/\mathrm{AGE}) + b_2(\mathrm{SDI}) + b_3(C) + b_4(S) + b_5(\mathrm{YR}) + b_6(\mathrm{YR}^2)$$

where

RW is the 5-year moving average FORDROUT-adjusted ring width (mm)

AGE is the age-class (20, 25, 30, 35, 40, or 45)

SDI is stand density index

C is the 3-year moving average of DISP values averaged over the 2 preceding years and the current year

S is site index

YR is calendar year

Several interaction variables (SDI × AGE, SDI × YR, and SDI × age × YR) were added to the model. After analysis of variance eliminated nonsignificant variables (Table 2), the regression equation was reduced to the following ($R^2 = 0.64$):

[1] $$\mathrm{RW} = 4.193 + 30.42(1/\mathrm{AGE}) - 0.111(\mathrm{SDI}) + 0.649(C) - 0.0378(\mathrm{YR})$$

TABLE 3. Ring widths (RW, mm) and ring areas (RA, cm^2), calculated using eqs. 1 and 2, associated with changes in stand age, stand density, and the passage of time, for constant average climate and mean tree diameter per age-class

Age-class (yr)	Tree diam. (cm)	1949			1984		
		Low SDI	Mean SDI	High SDI	Low SDI	Mean SDI	High SDI
20	14 RW	4.29	4.18	3.18	2.99	2.43	1.86
	RA	14.9	14.5	11.6	9.9	8.3	6.6
30	20 RW	3.78	3.56	2.67	2.46	1.79	1.35
	RA	16.9	16.2	13.6	11.9	9.9	8.6
40	24 RW	3.53	3.26	2.42	2.21	1.50	1.10
	RA	17.2	16.4	13.9	12.3	10.1	9.0

NOTE: SDI, stand density index. Low SDI is represented by class 2 and high SDI by class 12. Mean SDI values for 1949: age 20 = 3.0; age 30 = 4.0; age 40 = 4.4; and for 1984: age 20 = 6.8; age 30 = 8.0; age 40 = 8.4.

TABLE 4. Statistics for age-class 30 ring-width and ring-area regression equations; variables are listed in order of their contribution to sequential R^2 values

(A) Age-class 30 ring width

Variable	Mean	Coefficient	SE	P that $b = 0$	Sequential R^2
SDI	5.3	−0.099	0.021	<0.001	0.246
YR	72.1	−0.0407	0.0075	<0.001	0.450
C	1.04	0.653	0.233	0.050	0.467

NOTE: Data based on 83 observations (b_0 = 5.408). Calculated ring-width change from 1949 to 1984 is −1.43 mm, a 38% decline from the 1949 average of 3.57 mm, with SDI and C held at mean values.

(B) Age-class 30 ring area

Variable	Mean	Coefficient	SE	P that $b = 0$	Sequential R^2
DIAM	20.58	0.796	0.040	<0.001	0.439
SDI	8.13	−0.308	0.042	<0.001	0.508
YR	72.0	−0.155	0.025	<0.001	0.552
C	1.04	2.92	0.87	0.050	0.573

NOTE: Data based on 399 observations (b_0 = 5.70). Calculated ring-area change from 1949 to 1984 is −5.4 cm^2, a 36% decline from the 1949 average of 15.0 cm^2, with SDI and C held at mean values.

When C is omitted from the analysis, the linear and quadratic forms of YR are both significant, but R^2 is reduced slightly. Thus, the curvilinear effect of YR is accounted for by C.

The coefficients in eq. 1 were used to calculate time series from 1949 through 1984 for tree-ring widths for given ages and years and for constant mean stand density and constant normal climate (Fig. 5). Ring widths associated with these variables were calculated using eq. 1 (Table 3).

Autonomy of age-classes

Autocorrelation exists in dendrochronological studies because tree-ring measurements from the same trees are used as observations at more than one period of time. In this analysis, tree rings from the same stands are used at 5-year intervals as separate, independent observations for more than one time interval. Adjacent 5-year classes, for example, contain observations from many of the same plots. On the other hand, extremities of the age-classes 20 and 45 contain no plots in common.

A first-order multiple regression equation of the form

$$\mathrm{RW} = b_0 + b_1(\mathrm{SDI}) + b_2(C) + b_3(\mathrm{YR})$$

was calculated for each of the six age-classes separately, so that no autocorrelation existed within each analysis. Mean SDI per age-class, and constant climate, were substituted in the resulting equations to calculate ring-width changes from 1949 through 1984 for each age-class independently of the other age-classes. Table 4 gives the statistics for this analysis for age-class 30. Statistics were similar for all other age-classes. Thus, when calculated separately within each age-class, i.e., there is no autocorrelation, ring width is affected by the same environmental variables as when all age-classes are pooled.

Ring-area analysis

Changes in annual basal area (inside bark) increments, or tree-ring areas, were analyzed in a similar way to those for ring widths. Five-year age-classes of 5-year moving averages of these ring areas, in square centimetres, were FORDROUT-adjusted and used as the dependent variable in a multiple regression analysis for which all the following independent variables were found to be significant (Table 2):

$$[2] \quad \mathrm{RA} = 13.9 + 0.833(\mathrm{DIAM}) - 0.298(\mathrm{AGE}) - 0.331(\mathrm{SDI}) + 2.88(C) - 0.142(\mathrm{YR})$$

where DIAM is the diameter (cm) inside bark at breast height at that age and year. Coefficients of these five significant variables were used to calculate ring-area changes associated with tree diameter, stand age, stand density, climate, and the passage of time for the period 1949–1984 (Table 3).

The autonomy of age-classes for ring areas was analyzed in a similar way to that for ring widths, through separate regressions by age-class, using the form of eq. 2 without the variable AGE (in Table 4, age-class 30 is used as an example).

Results

Changes in stand density and their effect on tree rings

Mean SDI increased significantly within age-classes over the 36-year period. For example, stands of age-class 30 in 1949 averaged about 22 m^2 basal area per hectare for all trees, i.e., pines and hardwoods, 2.5 cm dbh and larger. In 1984, stands of age-class 30 averaged 28 m^2 basal area per hectare for all trees. Average numbers of stems 2.5 cm dbh and larger increased about 15% in these stands over the period. Moderate increases in stand density over time occurred in all six age-classes.

The effect on tree rings of these increases in average stand density is indicated by the coefficient for SDI in the regression equations. Within any calendar year, ring widths and ring areas vary by more than 50%, as SDI values vary widely from stand to stand. In addition, over the 36-year period the effect of the increase in average SDI value, from 4 in 1949 to 8 in 1984, results in an average ring-width decrease of about 12% and an average ring-area decrease of about 8% as a result of this variable alone.

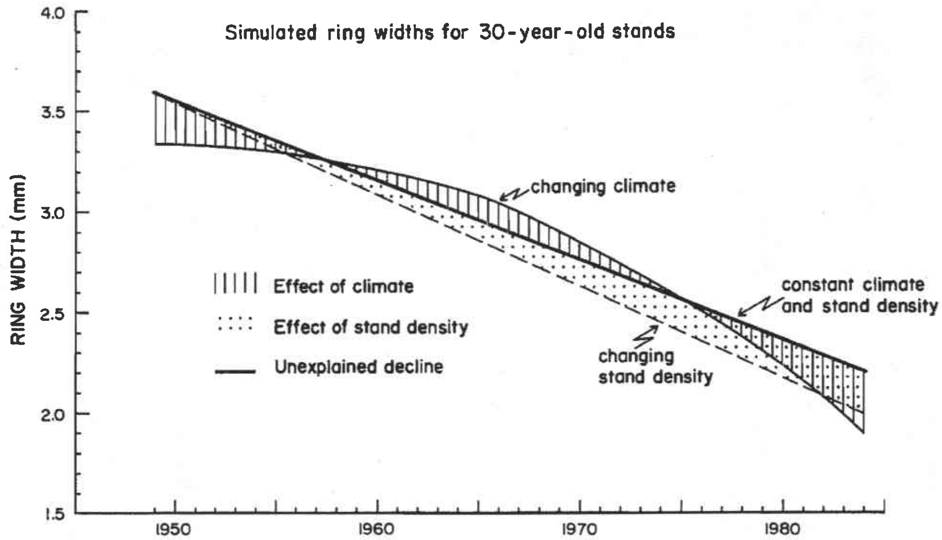

FIG. 6. Effects of regional climate and stand density, changing over time, on simulated ring widths for the 30-year age-class, calculated from eq. 1. Changing values for variables C and SDI are means for that age-class at 5 calendar year intervals.

The interactions SDI × AGE, SDI × YR, and SDI × AGE × YR did not significantly improve the R^2 value for the tree-ring models of eqs. 1 and 2. Therefore, the calculated declines in ring widths and ring areas resulting from changes in stand density over time are constant through all age-classes, and given stand densities early in the 36-year period have the same effect on tree rings as later in the period. Although the SDI × YR interaction is highly significant when used alone in lieu of SDI and YR separately, it did not provide a better model fit than the two individual effects in the linear model. In addition, principal components analysis and ridge regression analysis (Draper and Smith 1966) failed to allocate further the individual effects on ring width of increasing SDI over time and the passage of time alone.

Changes in sites and their effect on tree rings

There were 56 stands younger than 35 years of age in 1964 and 67 stands younger than 35 years in 1984. For each of these two time periods, approximately one-quarter of the plots were on sites of below-average quality, one-half were on sites of average quality, and one-quarter were on sites of above-average quality. There is a slight shift in site-class distribution to better sites later in the two-decade period compared with earlier. All stands were located on old-field sites. Site quality ratings indicate, if anything, that loblolly pine was growing on somewhat more productive sites in 1984 than in 1954.

In the regression analyses, S (site index) alone did not significantly influence tree-ring widths or areas. This site factor had previously entered the model through the FORDROUT adjustments to tree rings, a procedure apparently adequate to account fully for the effect of site through its interaction with climate.

Changes in climate and their effect on tree rings

Three-year preconditioned averages of the DISP regional climate simulation show clearly that the period 1949–1984 encompasses several distinct climatic intervals for the three-state Piedmont region (Fig. 3). The 10 years from 1950 through 1959 were consistently more droughty than normal, with generally unfavorable conditions for radial growth of the southern pines. This period includes the extreme drought of 1954 which occurred throughout the southeastern United States. For a long period from 1960 through 1979 growing conditions were generally favorable, with most years substantially wetter than normal. A few exceptions occurred during this period, such as a local drought in central South Carolina in 1962. In 1980, a severe drought occurred throughout the Piedmont, and the period from 1980 through 1983 was generally limiting to radial growth.

In the regression analyses, the 3-year moving average of DISP has a highly significant influence on ring width and ring area. This variable, C, termed regional climate, increases ring width and ring area by about 5% per year when there has been a favorable preconditioning, and decreases ring width and ring area by the same proportion when there has been an unfavorable 3-year preconditioning. Therefore, the accumulated effect of regional climate, changing from generally droughty to very favorable and then back to droughty over the 36-year period, modifies ring width and ring area to a curvilinear trend from 1949 through 1984 (Fig. 6). With regional climate constant at the long-term normal (DISP = 1.00), the regression equations calculate the independent effect of the passage of time (YR) on tree-ring development.

The passage of time and its effect on tree rings

Figure 5 illustrates simulated ring-width time series, calculated from regression equation [1], for stands aged 20 years in 1950, 1955, 1960, 1965, 1970, 1975, and 1980, and for stands aged 20, 25, 30, 35, 40, and 45 years in 1950. Lines connecting equivalent ages in these simulated time series illustrate a simulated decline in ring widths of 0.038 mm per year from 1949 through 1984 (Fig. 7). These simulations are for stands of mean stand density per age-class constant over time, and for a constant climate. For 30-year-old stands, with an average ring width of 3.6 mm in 1949, this decline in ring width amounts to 38% over the 36-year period, to 2.2 mm in 1984, or about 1% per year.

A similar decline is simulated for ring areas calculated from regression equation [2]. The average 30-year-old tree with diameter inside bark of 20 cm in stands of average den-

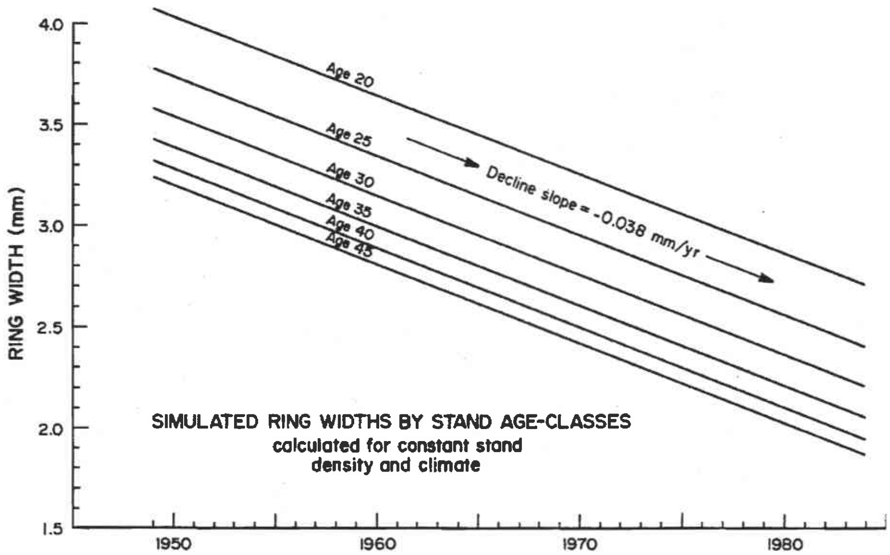

FIG. 7. Simulated ring-width decline from 1949 through 1984, by 5-year class, calculated from eq. 1. Stand density index is held at the long-term mean value for each age-class, and C is held constant at the long-term normal value.

sity had a ring area of about 14 cm^2 in 1949; 30-year-old trees of the same diameter had ring areas of 9 cm^2 by 1984 in stands of the same density and under constant normal climate. This represents a ring-area decline of 36% over the period, or exactly 1% per year.

Discussion and conclusion

Other dendroecological studies that establish growth changes related to regional changes in the environment have used long-term ring-width chronologies extending back to the turn of this century (reviewed by Fritts and Swetnam 1986). A preperturbation control period establishes the expected growth trend and is then statistically tested against a measured trend associated with an environmental change (Cook 1986; Kienast 1985). A different method is required for young stands with short time series (Zahner 1988). Natural stands of loblolly pine in the southeastern United States are not old enough to predate suspected environmental changes in the Piedmont region. Moreover, a regional decline in forest health associated with predisposing agents may gradually accumulate over time, precluding the relevancy of tree-ring indexing and response function procedures (Fritts 1976) that cannot identify such growth changes in young stands.

The dendroecological simulation of loblolly pine tree-ring chronologies from natural, undisturbed stands throughout the Piedmont shows that a significant decline in radial growth occurred over the 36-year period 1949–1984. This decline is not associated with changes in either site productivity or stand age. Piedmont upland sites are susceptible to drought as an ongoing predisposing stress factor (Manion 1981; Zahner and Myers 1986). The exceptionally dry years of the mid-1950s could have triggered a regional growth decline in Piedmont loblolly pine stands similar to the long-term regional declines in tree rings reported for *Quercus* species by Phipps and Whiton (1988) and Tainter et al. (1988) which began in the mid-1950s at widely separated locations throughout eastern United States. Climatic changes in the Piedmont ameliorated the decline in the middle of the period and increased it sharply later in the period. Without the cyclic impacts of favorable and droughty climate, the ring-width and ring-area declines are linear with time (Figs. 6 and 7).

The decline is partly associated with changes in stand density within age-classes, as both basal area and number of stems per hectare have increased significantly in these natural pine stands over the 36-year period. Ring widths in the early 1980s, therefore, were somewhat narrower on average than in the early 1950s, independently of stand age and tree diameter, because of the higher average basal areas and stocking levels supported by natural stands that were established and matured later in the period. The tree-ring simulations indicate that this change in average stand density with time results in decreases of about 12% in ring widths and 8% in ring areas over the 36-year period (Fig. 6).

The major decline simulated for ring widths (38%) and ring areas (36%) is associated with the passage of time, independently of the measured environmental and endogenous stand factors. From this simulation, it is concluded that trees in natural, even-aged stands of loblolly pine between the ages of 20 and 45 years in the Piedmont region of the southeastern United States were growing in the early 1980s at about two-thirds of the annual radial increment of equivalent trees in stands of the same age on the same sites 3.5 decades before.

The growth decline reported by Sheffield and Cost (1987) has also been verified recently by W. A. Bechtold, G. A. Ruark, and F. T. Lloyd (personal communication)[1] and F. T. Lloyd and T. A. Waldrop (personal communication),[2] who report serious reductions in basal area growth for natural stands of loblolly pine in the Piedmont region of Georgia and the coastal plain of South Carolina and

[1]W. A. Bechtold, G. A. Ruark, and F. T. Lloyd. 1989. Analyses of basal area growth reductions in Georgia's natural pine stands. Unpublished manuscript. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

[2]F. T. Lloyd and T. A. Waldrop. 1989. Comparing growth of natural loblolly pine over a 28-year span. Unpublished manuscript. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Virginia. After adjusting for periodic differences in site, stand density, mortality, and hardwood competition, they found that annual basal area growth was down 15–20% in 1972–1986 compared with 1956–1972. The regional climate change between these two periods may have been responsible for a portion of this reported growth decline, but as simulated in the present study, other significant causal factors remain unidentified.

In addition to climate as an exogenous time-related factor operating over the entire geographic area, the one man-caused exogenous factor that potentially affects all pine stands in the Piedmont region is atmospheric deposition. Schafer et al. (1987) report reductions in growth of juvenile loblolly pine under ambient levels of ozone stress in controlled field experiments in the Piedmont of North Carolina. It is well documented that ozone concentrations are high throughout forested areas of the Piedmont region (Pinkerton and Lefohn 1987; Rodgers and Chameides 1988), and any impact of this pollutant on forest health is likely to be time-related.

The simulated 36-year declines in ring width and ring area are time-correlated with changes in stand density and climate, and perhaps with other unidentified stress factors. As Piedmont pine stands passed from an unfavorable climate early in the period, radial growth may have failed to respond strongly to the favorable climate of the middle period, perhaps because of unidentified predisposing stresses combined with increases in stand density. As these pine stands later passed from the favorable climate era into the unfavorable later period, radial growth may have declined rapidly in response to the combined stresses of droughty climate, increases in stand density, and possibly regional ozone pollution. A significant portion of the simulated decline cannot be dismissed as climatic and competition effects. The regional trends in levels of ozone and other possible pollutants indicate that they should be seriously considered as correlative agents.

Acknowledgments

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