RESEARCH REPORT

A MODEL FOR TREE-RING TIME SERIES TO DETECT REGIONAL GROWTH CHANGES IN YOUNG, EVENAGED FOREST STANDS

ROBERT ZAHNER

Department of Forestry, Clemson University
Clemson, South Carolina 29634-1003

ABSTRACT

Time-related region-wide growth declines or increases due to environmental impacts are not readily detected in rings of young trees because the intrinsic age-related decrease in ring widths is too prominent. Standardization techniques often obscure gradual growth changes due to exogenous factors such as regional atmospheric deposition. The model presented here uses a linear aggregate analysis of ring widths that permits age to be held constant while time varies. Rigorous testing requires tree-ring observations from evenaged stands exhibiting a range of current ages normal for the species and region. With age held constant, the key variable is simply the calendar year to which given rings are dated, a measure of the passage of time. An application of the model is given in which a 36-year growth decline is identified in 20- to 40- year-old *Pinus taeda* L. in the southeastern United States.

INTRODUCTION

Tree-ring models that establish growth changes related to changes in the environment must always account for the intrinsic effect of ring width decreasing with age due to increasing girth. In old trees this age-related trend has often long stabilized, so that long term chronologies may permit comparison of ring widths between two time periods without serious distortion due to increasing girth. Using "standardization" techniques (Fritts 1976), a calibration period can establish the expected growth trend in older trees and is statistically tested against a measured trend associated with an environmental change, or post-perturbation growth, all recorded in the rings of the same trees (Fritts and Swetnam 1986).

Younger stands of trees, however, may not predate suspected environmental changes, and the age-associated decrease in ring widths is often the most significant growth trend in these short chronologies. Moreover, regional environmental changes, such as non-point source atmospheric deposition, may accumulate gradually over time and may not be detected as date-related events that trigger sudden changes in ring widths of the same trees. A method is needed that holds age constant while time varies, comparing ring widths of equal aged trees at different periods of time. This report suggests a model in which tree rings of a given age in young, evenaged forest stands are tested for the impact of suspected time-related environmental changes on ring width.

METHODS

The model requires absolutely-dated tree-ring measurements from many forest stands, located randomly throughout the region of interest, exhibiting as broad a range of current ages as normally occurs for the species and stand type. For example, most commercially important forest types in eastern North America, the southern and northern pines, the upland oaks, the cove hardwoods, and the northern hardwoods, occur commonly in evenaged stands currently aged from early regeneration to commercial rotations of 40 to 60 years. Short-term tree-ring chronologies from such stands must obtain replication for statistical testing from a large number of field plots. Cook et al. (1982) suggest that tree-ring studies in young forests typical of eastern North America utilize limited numbers of increment cores from each of a large number of field locations. Each evenaged stand becomes a separate observation for a given stand age.

Because juvenile trees younger than 10 to 15 years may contain a large proportion of reaction wood, sample stands should be sufficiently old to support closed canopies with stabilized dominant and codominant crown classes. This minimum age varies with species, site, and geographic location and can generally be determined from the tree-ring measurements. An adequate number of field plots, each representing a definable evenaged stand on a specific site, might be no more than 50, sampling the full range of age classes that is normal for the forest type and region.

Increment cores are extracted from dominant and codominant trees in each stand, prepared for measurement, crossdated and measured, all by standard techniques (Fritts 1976, Phipps 1985). Ring widths from all cores in each stand are averaged by collating the absolutely-dated ring measurements for all calendar years represented in the series. Stand, site, and climate data (for example, stand basal area, site index, and Palmer drought severity index) are collated for each stand by each calendar year for which there is an average ring-width measurement.

Graybill (1982) and Cook (1986) have presented aggregate models to express the potential components of tree-ring variation. For the short-term chronologies of young evenaged stands, such a model must include a term for calendar year to express the effect of the passage of time. The dependent variable in this aggregate model is RW, representing a ring-width measurement accurately dated to the calendar year t:

$$RW_t = f[Age_t, B_t, C_t, S_t, YR_t, E_t]$$

where:

Age = The age-related growth trend value in year t that is shared by all sampled trees of a given species on a given site.

B = The endogenous growth pulse within the given stand, originating from changes in competition, stand structure, and stocking levels or other forces acting on sampled trees in year t.

C = The climatically-related growth variations common to a stand of trees in year t, including current weather, lagged accumulative preconditioning climate, and the interaction of climate with a given site.

S = Independent site-related growth variation, usually ongoing over the life of the stand, often constant for all t years.

YR = A measure of the independent effect on growth of the passage of time, in year t, unrelated to the age of the stand, originating as an on- going exogenous pulse from outside the stand.

E = The more or less random variations representing growth- influencing factors in year t unique tó each stand and sample trees.

Each component must be identified, measured, and collated with each average annual ring width of each stand. Functions for the various components may take linear or exponential forms, and may interact with one another. This paper will not discuss such procedures, as they are complex and different for each forest type and region of interest. Many previous publications discuss these procedures in detail, presenting methodology for quantifying and testing the many components of tree-ring variation (Fritts 1976, Graybill 1982, Cook 1986, Fox et al. 1986, Fritts and Swetnam 1986, Zahner et al. in press).

In the present model, beginning with the current age of each stand when sampled, a time series for average annual ring widths is established by age classes. Ages are assigned to each ring width for each calendar year back as far as the post-juvenile chronology extends for a given stand. Five years constitute a satisfactory age class interval; thus five-year moving averages are calculated for each stand to establish the ring width trends over calendar years (Figure 1). For example, if stand 2 is 38 years old in 1984 when sampled, it will be represented in the model by average ring widths at four age classes: age 20 in 1966, age 25 in 1971, age 30 in 1976, and age 35 in 1981. In a field sample, if current ages of all stands are well distributed between 15 and 50 years, and the current year is 1988, then

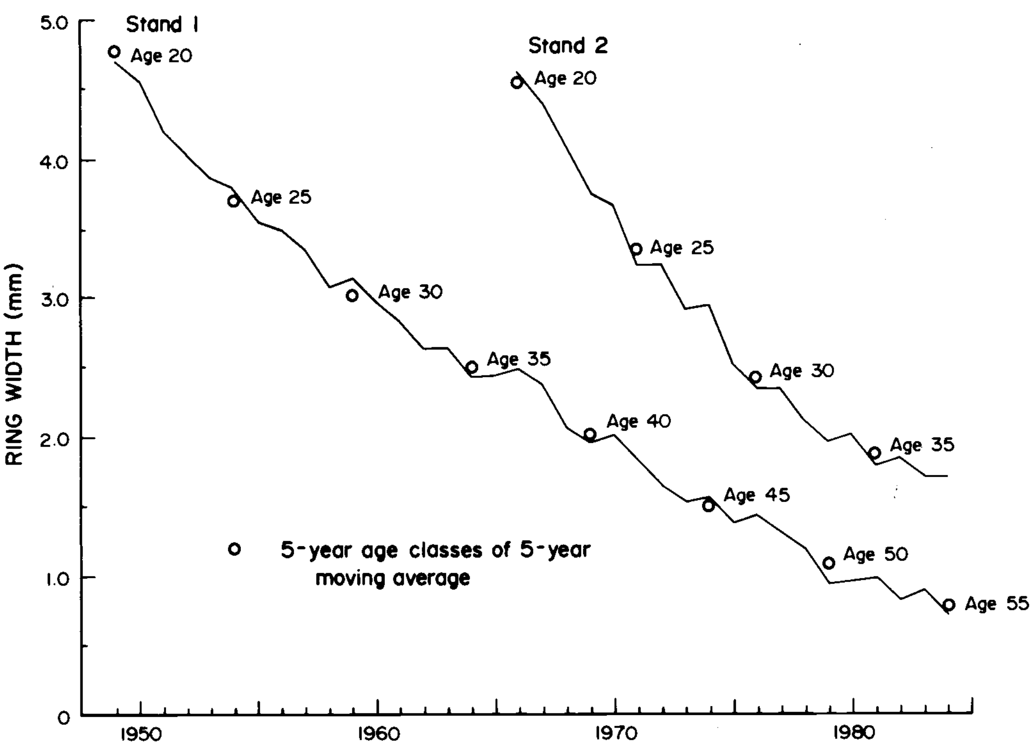

Figure 1. Examples of annual 5-year moving averages calculated for ring widths in two stands with chronologies ending in 1984. Ring widths previously adjusted for annual variance due to climate. The plotted age classes are 5-year averages of the annual 5-year moving averages. The age classes establish the ring-width trend that includes both the intrinsic age-related decay curve and any long-term changes in growth related to region-wide environmental impacts.

stands in the 20-year-old class occur dispersed throughout the 30 years from 1959 through 1988. Stands in the 25- and 30-year age classes are dispersed through shorter time periods, 1964-1988 and 1969-1988, respectively.

The independent components B_t and C_t in the aggregate model must also be averaged for those years comprising each 5-year age class. Establishing a relative stand density index is helpful for assigning the endogenous growth pulse by 5-year classes where annual measures are not available for averaging. The normally large variation in tree rings associated with annual weather variation can be reduced first on a year-to-year basis, before averaging ring widths by age classes (Zahner and Grier in press).

Multiple regression is employed as an appropriate technique to fit the field and laboratory data to a time trend (Draper and Smith 1966), such as the following ring-width (RW) model:

$$RW = b_0 + b_1(1/Age) + b_2(B) + b_3(C) + b_4(S) + b_5(YR)$$
$$+ b_6(YR^2) + b_7(Age \times YR) + b_8(B \times YR) + b_9(C \times YR).$$

The independent variables are tested for their contributions to ring-width variance, the non-significant variables eliminated, and the coefficients calculated for significant variables.

The key variable in this model is YR, the effect of the passage of time on ring width variation. If the coefficient for this variable, or any of its interactions, is not significant within any age class, the ring widths have not changed with the passage of time for the data set tested. A data set that has significant coefficients for YR and for any of the other non-interactive variables in the above equation, i.e., b_1 through b_5, provides a ring-width time series that quantifies lineal growth changes over time.

Figure 2 illustrates two hypothetical possibilities, when both the YR and Age x YR variables are significant, with time series calculated for stands aged 15 years old in each of 1957, 1967, and 1977. These stands are simulated to be aged 25, 35, and 45 years old, respectively, when sampled in 1987. In these examples, the endogenous growth pulse (variable B) is held constant over time within each age class, climate (C) held at the long-term normal, and site (S) held at the average for the region. In example A, lines connecting the corresponding age classes show a ring width decline for stands older than 20 years but not for younger stands. In example B, there is an increase in ring widths for stands younger than 30 years but not for older stands. Many other possibilities exist for combinations of significant coefficients.

AN APPLICATION OF THE MODEL

In a recent dendroecological analysis of natural stands of loblolly pine (*Pinus taeda* L.) in the Piedmont region of southeastern United States, Zahner et al. (in press) applied this time series model to tree rings from 131 stands between the ages of 25 and 80 years when sampled in 1985. Ring measurements in these young stands provided sufficient data to extend the absolutely-dated chronology back 36 years to 1949. These were USDA Forest Service inventory plots that had been remeasured for endogenous stand conditions four times at 10-year intervals since the early 1950's decade. Six 5-year age classes from 20 to 45 years were established, the endogenous pulse was entered as an index of basal area and number of trees per hectare for each age class in each stand extending back through the 36-year period, climate was modeled from weather data provided from NOAA data files (Zahner and Grier in press), and site quality was obtained from soil and site descriptions of each stand.

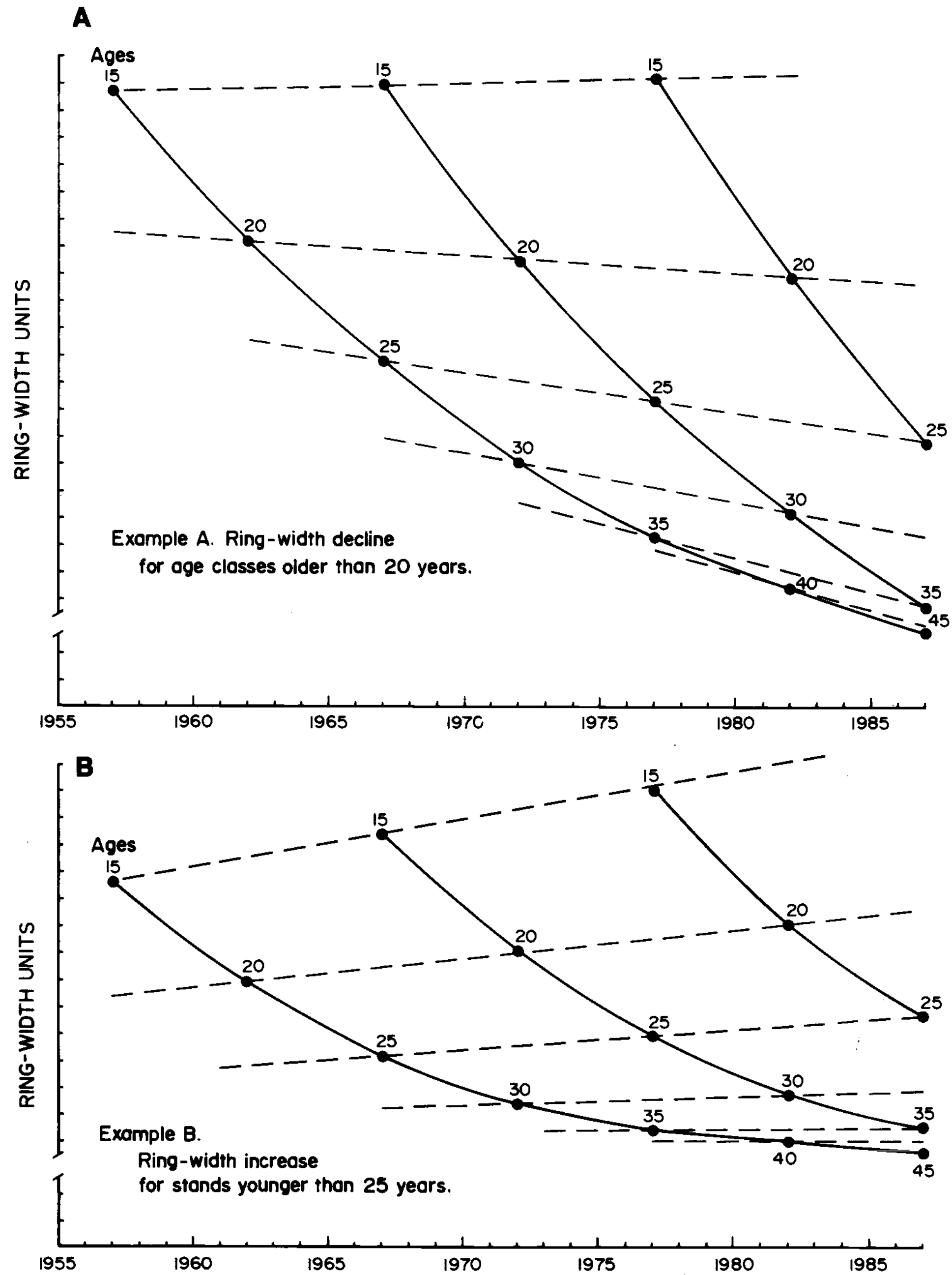

Figure 2. Two hypothetical solutions for the ring-width model. Both examples simulate time series for stands aged 15 years old in each of 1957, 1967, and 1977, with chronologies extending to the end of 1987, the assumed sampling date for the observations from which the model is calculated. The YR coefficient is negative in example A and positive in example B; the YR x Age coefficient is negative in both examples.

Tree rings were adjusted for all of the above components to test for the residual effect of the passage of time. For average loblolly pine stand conditions on average Piedmont region sites with trees growing under constant normal climate, the following linear relationship was found highly significant ($R^2 = .62$):

$$\text{Ring width (mm)} = 4.487 + 30.0\ (1/\text{Age}) - 0.0395\ (\text{YR})$$

where:

YR = Calendar year between 1949 and 1984 (i.e., 49-84).

This relationship is illustrated in Figure 3, (above) the time series and (below) the ring-width decline by age classes. The Age x YR variable was not significant in this analysis; therefore, the calculated decline is parallel for all age classes. The linear decrease in ring widths is about 1% per year over the 36-year period for average age stands.

In all such applications the impact of the YR component cannot be quantitatively established if there remains a large variation in ring widths unaccounted for by other factors. Success of the model, therefore, requires for each stand adequate endogenous, site, and climatic relationships over sufficient time spans to match the tree-ring record. Site, once measured, is constant for a given stand. Climate variables, although not measured on site at each stand, are always available regionally in the United States from the National Weather Service and are often available within reasonable distances from individual stands. Endogenous stand data are more difficult to acquire, even for short time spans, for reconstructing the development of young stands to maturity. Continuous or periodic forest inventories can provide such data and are available from government agencies such as the USDA Forest Service or the TVA in the United States, as well as from many industry, military, state, and university forest management offices.

The choice of environmental variables to represent the components of tree-ring variation is extensive and often dependent on the experience and interpretation of the investigator in tree growth-environment relationships. Environmental impact interpretation must be consistent with intrinsic responses of forest types, tree species, and geographic location. Such models must be based on adequate replication to reduce ring width variance attributable to the measurable environment sufficiently to detect growth changes attributable to the unmeasured environment, or the passage of time

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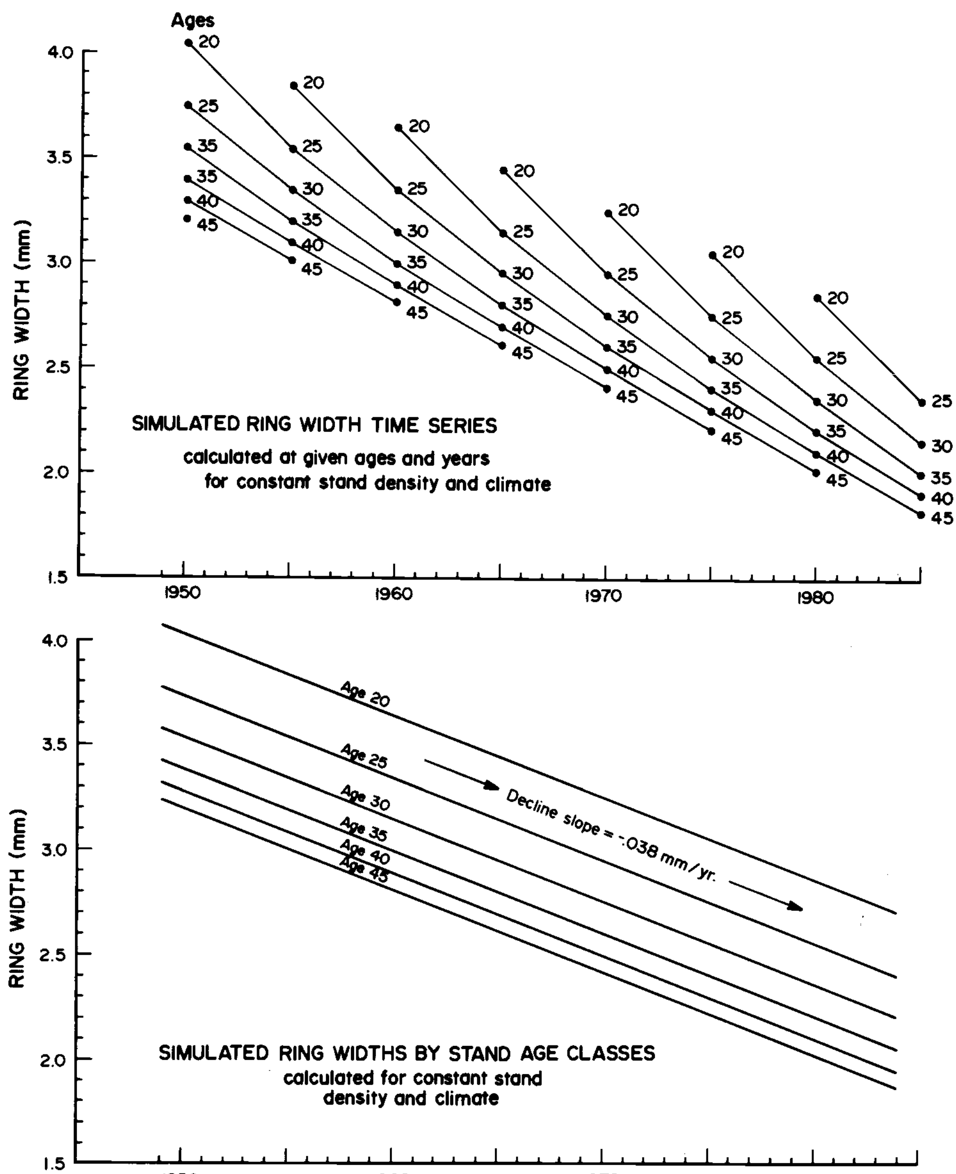

Figure 3. Solution for the treering model calculated from 131 loblolly pine stands in the Piedmont region of southeastern United States. (Above) Time series for stands aged 20 years old in each of 1950, 1955, 1960, 1965, 1970, 1975, and 1980, and for stands aged 25, 30, 35, 40, and 45 years old 1950. (Below) The ring-width decline identified from the solution above.

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