

A TIME SERIES ANALYSIS APPROACH TO  
TREE RING STANDARDIZATION

by

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## CHAPTER 2

### A LINEAR AGGREGATE MODEL FOR TREE-RING SERIES

#### Introduction

Consider a single tree-ring series along a single radius as a linear aggregate of several subseries representing the sources of variance found in the composite series. Let this aggregated time series be expressed as

$$G = C + A + D1 + D2 + E$$

where:

- G = the well-dated tree-ring widths measured along a single radius,
- C = the climatically-related growth variations common to a stand of trees including the mean persistence of these variations due to physiological preconditioning and interaction of climate with site factors,
- A = the age related growth trend,
- D1 = the endogenous disturbance pulse originating from forces within the forest community,
- D2 = the exogenous disturbance pulse originating from forces outside the forest community,

E = the series of more or less random variations representing growth influencing factors unique to each tree or radius within the tree.

The assumption of linearity and implicit independence between the subseries is a necessary oversimplification for the moment. However, the purpose of this model is not to describe exact relationships between the subseries. Rather, it allows for a discussion of certain properties of each component separately from the others as a necessary step in developing a standardization method that models the nature of the tree-ring series more adequately.

#### Subseries C--The Common Climate Signal

The climatically-related subseries, C, reflects certain broad-scale meteorological variables which directly or indirectly limit the growth processes of trees in a stand. These variables are assumed to be uniformly important for all trees of a given species when the site characteristics of the stand, such as hydrology, elevation, exposure and soil, are more or less homogeneous. The biology of the tree governs its capacity to respond to climate. This in turn determines the "climatic window" (Fritts, 1976, p. 238) through which climate variables create similar patterns of wide and narrow rings in different trees when matched contemporaneously. This is the phenomenon that enables cross-dating. Although cross-dating is normally associated with high-frequency change in ring width, there are also many lower-frequency variations of climate that pass through the climatic window which can also be shown to be in agreement between the trees (Fritts, 1976).

The input that produces C is assumed to involve weakly-stationary stochastic processes. That is, its mean and variance are independent of time, and the series evolves through time in a probabilistic fashion. Because of the previously mentioned feedback mechanisms affecting the climate system, the climatic signal in C will often be non-random in an autoregressive sense. This has been shown to be the case for temperature data (Jones, 1964) and Palmer drought severity indices (Katz and Skaggs, 1981), although precipitation is more frequently random (Salas et al., 1980, p. 51). When the autoregression is positive, the variance of C will be concentrated in the lower frequencies of its variance spectrum. Such series are often described as "red noise" processes (Gilman, Fuglister, and Mitchell, 1963) due to the analogy between low-frequency variance and long wave-length red light.

Frequently, the persistence observed in C will be much greater than that which can be accounted for by the persistence in climate (Matalas, 1962; Meko, 1981). This inflated persistence in the ring-width series is generally thought to come about from a variety of factors often involving the physiological preconditioning of the tree-growth system by previous environmental conditions (Fritts, 1976) and from site factors such as soil hydrology (Meko, 1981) which create lags in the tree-response system. Meko (1981) also contends that some of the excess persistence is due to residual non-climatic growth variations not removed during standardization. This contention implicitly recognizes that there must be inadequacies of current standardization methods which I have discussed in Chapter 1. Any differences between the persistence

structure of climatic variables which produce  $C$  and  $C$ , itself, can of course be adjusted for during the transfer function modelling phase of dendroclimatic reconstructions (Stockton, 1975; Fritts, Lofgren and Gordon, 1979; Meko, 1981). Meko (1981) has demonstrated how Box-Jenkins models can be used in this regard. This type of analysis occurs subsequent to standardization. Discussion of various approaches to transfer function modelling are clearly outside the current topic and will not be considered further. From a climatological point of view, the assumption of weak stationarity for the input leading to  $C$  is flawed because the climate system probably never reaches a true equilibrium state and appears to be inherently non-stationary over very long time periods. Thus, a 400-year tree-ring series could have, superimposed on its age trend, a very low-frequency climatic fluctuation on the order of several centuries long. In this case, the series would be non-stationary due to the presence of two different, but not necessarily uncorrelated, components. But in another sense, the assumption of weak stationarity is reasonable for the usual time spans under consideration. Variance spectrum analyses of climatic and proxy climatic series for the Holocene (Kutzbach and Bryson, 1975) show that such series generally have moderately "red" ( $\rho=0.5-0.7$ ) spectra for time periods of 100 to 1000 years. This level of redness is well within the bounds of stationarity for a first-order autoregressive process (Box and Jenkins, 1970). Since old-growth stands of trees rarely exceed 1000 years in age, the first two moments of  $C$  may not behave differently in a statistical sense from a weakly-stationary process. Because there is strong biological basis for

expecting an age trend, virtually all tree-ring chronologies are detrended with the realization that some long-period climatic information may be lost.

#### Subseries A--The Age Trend

The age trend, A, was described earlier as being a monotonically non-increasing function of time which could be characterized often by a deterministic growth function of linear or exponential form. While this description holds well for trees growing in open-canopy situations, it must be generalized to allow for the occurrence of a variety of linear and curvilinear age trends of arbitrary slope sometimes found in trees from closed-canopy forests. Shade tolerant species such as eastern hemlock and red spruce may require many decades of growth to achieve a co-dominant position in the canopy. During these years of subordinate canopy position, the general trend in radial growth will often be positive as the suppressed trees grow upward into more favorable regions of the canopy. Once it becomes established in the canopy, the rate of growth may decline in the normally expected way. Since both the upward and downward trend is, again, clearly associated with increasing age, a more general age trend model should be included which may allow for linear or curvilinear trends of arbitrary slope and shape.

As noted in Chapter 1, many mathematical functions are available that seem to fit certain kinds of age trends well. For example, quadratic and power functions are reasonable alternatives to the negative exponential curve in some cases. The model for A should serve only to detrend a series and stabilize its variance to some degree. If we

define trend in mean according to Granger's (1966) definition as comprising all frequency components with wave-lengths exceeding the length of the observed time series, then linear, quadratic, exponential, and power functions are all possible models of A. They will not remove any climatic information that is resolvable from the age trend.

#### Subseries D1 and D2--The Endogenous and Exogenous Disturbance Pulses

The non-climatic variance accounted for by the disturbance pulses, D1 and D2, can be split into two general classes of disturbance: endogenous and exogenous (Bormann and Likens, 1979; White, 1979). Conventionally, they are differentiated by the causal mechanisms involved, i.e. forces internal to the forest community versus forces external to it, although these differences become quite blurred upon investigation (White, 1979). In the context of tree-ring standardization, another differentiating feature is pertinent: areal extent of impact. As will be described, this feature lies at the crux of the standardization method being developed here.

Like the age trend, D1 and D2 can be modelled as smooth processes. Collectively, they have been modelled deterministically using least square curve-fitting (e.g. Fritts, 1976, p. 164; Warren, 1980) and stochastically using digital filters (e.g. Bitvinskis, 1974; Cook and Peters, 1981), but the result is always a smooth, continuous curve for approximating a disturbance pulse. Superimposed upon this curve will be the higher-frequency climatic variations of C. However, because the duration of a disturbance pulse may be short compared to the length of the tree-ring series, it may be superimposed upon lower-frequency clima-

tic fluctuations as well. The shape of a disturbance pulse will also be much more variable than an age trend because a disturbance may cause growth suppression or acceleration depending on its relationship to the tree and the nature of its effect.

Endogenous disturbances are caused by factors related to characteristics of the vegetation which are independent of the environment (White, 1979). Disturbances which are often described as such in closed-canopy forest communities occur when dominant overstory trees senesce, die and topple as a natural consequence of competition, aging and stand succession. Although the senescence and death of old-age trees from internally caused factors seems biologically reasonable, it rarely occurs without the impetus of external environmental factors such as insect attack, drought and windthrow (White, 1979), hence, the difficulty in differentiating endogenous from exogenous disturbances. The removal of individual dominants creates gaps in the canopy for suppressed understory trees and adjacent codominants to grow into. These gaps also provide valuable seed beds for reproduction and regeneration. The sudden increase of available light and soil moisture may mean a dramatic increase in radial growth over several years for previously suppressed trees as they compete for dominant positions in the canopy gap. This model for structural changes in forest communities is called gap-phase reproduction by White (1979) and gap-phase replacement by Bray (1956) and Spurr and Barnes (1973, p. 344).

In the context of tree-ring standardization, truly endogenous disturbances can be expected to occur randomly in space and time in



forest communities. That is, the loss of a dominant tree in one section of a stand is not likely to be related temporally or spatially to similar losses at widely separated locations in the stand. This assumption immediately suggests that the resultant truly endogenous disturbance pulses will rarely be synchronous among distant trees in a stand except by chance alone.

Little data exists for estimating the frequency of occurrence of endogenous disturbances and the gap-sizes produced by them. However, a study of natural disturbances by treefalls in Lilley Cornett Woods (Romme and Martin, 1982) does shed some light on this matter. Lilley Cornett Woods is a 104-hectare tract of old-growth mixed mesophytic forest in eastern Kentucky. The dominant tree species are American beech (Fagus grandifolia Ehrh.) and white oak (Quercus alba L.). Over a period of eight years, 77 treefall events occurred, 66 by single trees and eleven by 2-3 trees. The major cause of treefall was ascribed to high-speed, short-duration winds. The area of each gap produced by treefall was carefully measured. The gaps ranged from  $74\text{m}^2$  to  $1235\text{m}^2$  in size with a mean of  $374\text{m}^2$  and a median of  $307\text{m}^2$  (Romme and Martin, 1982). A histogram of gap-size classes as a percent of all gaps indicates that the distribution is highly skewed. The mode lies within the  $101\text{-}200\text{m}^2$  and  $201\text{-}300\text{m}^2$  gap size classes which account for 46% of all gaps. A reasonable estimate of the gap size mode is  $200\text{m}^2$ . On the assumption that the gaps do not overlap, the radii of gap influence for the mode, median and mean are approximately 8m, 10m, and 11m, respectively. Thus, to minimize the probability of coring trees that are

affected by the same endogenous disturbance, trees separated by at least 16-22m should be cored. Only the trees tangential to a gap would be affected using this criterion.

In the 104 hectares of Lilley Cornett Woods, there are 2673-5000 potential gaps using the 200-374m<sup>2</sup> gap-size estimates. Allowing for an average of ten gaps/year (based on 77 tree-falls in eight years), only 0.2-0.4% of the canopy area is lost by tree-falls each year. This percent is lower than the percent of trees affected by a gap because several trees may grow around a gap perimeter. However, even if the number of affected trees is as large as 5, the percent of all trees affected by treefalls each year is still only around 1-2%. Thus, the probability of synchronous endogenous disturbance pulses in tree-ring series from Lilley Cornett Woods is quite small. This conclusion should hold for old growth stands in general where the dominant tree species are long lived and the stand is large relative to the gaps produced by treefalls.

Since the presence of D1 in the aggregate should impart more differences than similarities among a spatially broad sample of tree-ring series, an obvious approach to the standardization problem is to identify and remove only these differences. From the standpoint of minimal loss of climatic information, the identification and removal of low-frequency differences has obvious appeal because they cannot be logically related to fluctuations attributable to C. It is interesting to note that Dr. Edmund Schulman of the Laboratory of Tree-Ring Research used this concept in the pre-computer days of dendrochronology when he graphically standardized tree-ring series (B. Bannister, pers. comm.).

By plotting all of the series together, Schulman was able to identify significant differences and modify the standardization curves to remove localized low-frequency fluctuations which did not agree among all series. The simultaneous scrutiny of tree-ring data during standardization is sometimes omitted today because of the large number of series being standardized. However, a careful examination of the fitted growth curves is advised (Fritts, 1976) and some workers do remove data that are not adequately modelled by the growth function, or they vary the growth function that is used. Often they will standardize a sample several times until the major outliers from the growth curve are identified and removed or corrected (Fritts, 1976). This is a cumbersome and sometimes burdensome process.

Exogenous disturbances are caused by environmental forces which lie external to and are independent of the vegetation (White, 1979). Unlike endogenous disturbances, these disturbances have many possible causal agents which can affect large areas of forest. Some of the important agents are fire, windstorm, ice storm, disease and insect infestation. For a complete review of exogenous disturbance agents, see White (1979). Because an exogenous disturbance can be very extensive, the resultant disturbance pulse, D<sub>2</sub>, may occur contemporaneously in virtually all affected trees in a stand. This presents obvious difficulties for standardization for these contemporaneous pulses may be impossible to distinguish from common low-frequency fluctuations of C.

The frequency of a specific exogenous disturbance will generally be inversely proportional to its magnitude and is highly dependent on

such factors as species composition, topography and geographic location (White, 1979). For example, pitch pine (*Pinus rigida* Mill.) and jack pine (*P. banksiana* Lamb.) are shade-intolerant species which require frequent fire to maintain their communities (Fowells, 1965). Thus, the frequency of fire in these communities is likely to be high. In contrast, the fire recurrence interval for northern hardwood-conifer forests in New England may be several hundred years long (Bormann and Likens, 1979). The effects of fire will greatly depend on the severity of the burn. Frequent ground fires may benefit growth of shade-intolerant species by destroying understory growth, reducing root competition for moisture and recycling nutrients trapped in forest litter. More severe fires may impair subsequent growth if some foliage is killed by heat or flames and the cambial layer is scorched. If burns are much more severe than this, the stand may be destroyed outright and the exogenous disturbance problem is moot.

Insect infestations will have variable effects of forest stands depending on the severity of injury to host species and indirect effects on non-host species (Brubaker and Greene, 1979; Wickman, 1980). Phytophagous insects reduce the photosynthetic area of host species and thus cause reductions in carbohydrate production for ring formation. Conversely, growth of non-host species in an infested stand can actually improve because host-tree defoliation reduces competition for light, water and nutrients (Wickman, 1980). Fortunately, many tree species are able to withstand light to moderate amounts of defoliation without showing a detectable reduction in radial growth in the lower trunk of the

tree (Koerber and Wickman, 1970; Brubaker and Greene, 1979). The defoliation effect is most apparent in the rings of the upper bole and branches. This is fortuitous because virtually all tree-ring specimens are taken from breast height or below on the bole. But this also suggests that defoliation effects will show up more frequently in the earlier segments of tree-ring chronologies because the crowns of trees, when younger, will be closer to the breast height region of the bole sampled by dendrochronologists.

Sampling strategies can be designed to minimize the probability of some exogenous disturbances like fire and insect infestation. Stands isolated by water or barren expanses of rock are less likely to be affected by regional fires, for example. Another approach is site redundancy whereby stands on similar but geographically separate sites in the same region are sampled with the hope that a stand disturbance peculiar to one site can be identified. Insect infestation effects may be identified by sampling host and non-host species on the same or nearby sites. These approaches do not actually solve the problem of identifying exogenous disturbance pulses during standardization. They only reduce the problems. Without any knowledge of large-scale disturbances that have affected a stand, a better solution to this problem does not seem possible.

Since the importance of D2 is extremely difficult to establish because of its dependence on such factors as the frequency and magnitude of the event, the causal agent, tree species, site topography and geographic location, it will be assumed to have a minimal contribution to

G. This assumption is valid only in the sense that, if present, D2 may be very difficult to differentiate from C during standardization and should, therefore, be regarded as a possible climatic fluctuation until proven otherwise by comparison to C in nearby sites and in different species. This is the rationale for using a number of chronologies for different species and sites in transfer function analysis (Fritts, 1976).

#### Subseries E--The Random Variance

The last subseries, E, is the more or less random variance in the radial tree-ring series which represents such variables as localized responses to micro-environmental factors and variations in circuit uniformity which are unrelated to the variance accounted for by C, A, D1 and D2. This variance is assumed to result from serially uncorrelated events affecting each tree which are spatially uncorrelated within the stand of trees. The standard way to reduce this random variance is through replicate sampling (Fritts, 1976). That is, a number of trees are sampled (say, 20 to 40) from a forest stand and standardized. The results are averaged together to form a mean-value function for the site.

The linear aggregate model is useful for describing the concept of the signal-to-noise ratio (SNR) in tree-ring series. For example, a semi-arid site tree-ring series will be an aggregate of C, A and E with D1 and D2 assumed to be negligible, minimized or absent. After A has been removed, the climatic SNR is the ratio of the variances of C and E. As pointed out by DeWitt and Ames (1978), this ratio will ordinarily be

considerably higher in semi-arid site chronologies than in mesic forest-interior chronologies. Given the inadequacies of current standardization techniques, it is likely that the SNR of forest-interior chronologies can be increased appreciably by improving the standardization model.

### Conclusion

The linear aggregate model has identified several discrete classes of variance which can be found in a generalized ringwidth series. The two classes which have created the principal difficulties in standardizing forest interior ringwidths are the disturbance pulses, D1 and D2. The likelihood of significant non-synchronicity between endogenous disturbance pulses in a stand of trees offers a conceptual approach to optimally removing this class of non-climatic variance. That is, remove only those fluctuations that differ from tree to tree. In the next chapter, a method is developed which is based on this concept.