To the Graduate Council:

I am submitting herewith a thesis written by Donald Gregory Barlar entitled "Temporal and Spatial Variation in Annual Growth of Yellow-poplar *(Liriodendron tulipifera L.)* at Walker Branch Watershed, Tennessee." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

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TEMPORAL AND SPATIAL VARIATION IN ANNUAL GROWTH OF YELLOW-POPLAR *(LIRIODENDRON TULIPIFERA* L.*)* AT WALKER BRANCH WATERSHED, TENNESSEE

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ABSTRACT

Tree-ring increment cores were collected from 106 yellow-poplar (*Liriodendron tulipifera*) trees at Walker Branch Watershed, which is near Oak Ridge, Tennessee. Tree-ring widths were measured and converted to basal area increments (BAI's). BAI data were used to assess the relationship between temporal and spatial variation in moisture availability and variation in annual growth indexed by BAI. There are two major long-term growth trends in the mean BAI chronologies. These trends are an increase in BAI that occurs between 1961 and 1985 and a major decline in BAI that begins in 1986. Both of these trends are related to changes in climate. The first trend is associated with the climate becoming wetter than normal and the second trend is associated with a severe drought that occurred between 1985 and 1988. In 1989, the drought ended and climate became normal to wetter than normal; however, BAI did not recover after the drought ended. It is argued that the growth decline that lasted throughout the 1990's is a result of damage to the trees caused by extreme drought stress. The study also found that fine-scale differences in topography are related to variation in BAI. Topographic index, $\ln(\alpha/\tan\beta)$, was used to estimate the average moisture availability of the tree locations on Walker Branch Watershed. Xeric locations on Walker Branch Watershed have higher coefficients of variation in BAI than did mesic locations. Using multiple linear regression to perform response function analysis, it is shown that mean BAI chronologies from xeric locations have a higher association with variance in monthly climate variables than do mean BAI chronologies from mesic and intermediate locations.

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CHAPTER I

INTRODUCTION

Yellow-poplar (*Liriodendron tulipifera*), also known as tulip-poplar and tuliptree, is widely distributed throughout the eastern United States. Yellow-poplar grows over a variety of site conditions but is strongly adapted to moderately moist, loose, well-drained soils (Olson 1969). However, it does not grow well in very dry or very wet situations (Beck 1990). This sensitivity to moisture availability means that annual growth is likely to respond to differences in temporal and spatial moisture availability.

As a spatial characteristic such as topography varies, the site factors associated with topographic location vary as well. For example, a southwestern slope is sunnier and drier than a northeastern slope because the southwest aspect increases the solar intensity, which increases the dryness of the soil. When an environmental variable, such as solar intensity which affects moisture availability, changes across the landscape then the annual growth of yellow-poplar across the landscape should change as well.

Similarly, temporal variation in annual growth associated with temporal changes in climate is likely to vary across a range of topographic positions. For example, a tree situated on a ridge should be more sensitive to variations in rainfall than should a tree situated in a valley. A tree on the valley floor should have a steadier supply of water due to the tree's location on deeper soils and its proximity to the water table and streamflow; therefore, its growth rate should vary less from year to year than a tree situated on a

ridge. A tree on a ridge will have more moisture available for growth during a wet season than it would during a dry season; therefore, its rate of growth should be highly variable as rainfall increases or decreases across subsequent growing seasons.

Much is understood about variation in annual growth of tree species distributed across moisture gradients in semi-arid regions. Dendrochronologists have known for nearly a century that isolating climatic variation for measurement requires finding trees that are located on dry sites (Fritts 1976). A scientist interested in maximizing the variance in radial growth due to climate would not select trees that were growing in riparian zones. Though much is known about variance in growth of trees in the semi-arid regions of the southwestern United States not nearly as much is known about variance in growth of trees in the mixed mesophytic hardwood forests of the eastern United States. The challenge of my study is determining how annual growth varies from one topographic location to another in a tree species, such as yellow-poplar, growing in a humid mixed-mesophytic hardwood forest in the southern Appalachian region. In this region, rainfall is plentiful and even the most xeric ridge sites would be characterized as moist by southwestern United States standards. However, yellow-poplar, being adapted to the environment of the southern Appalachian region, should respond to the fine scale differences in moisture availability due to changing topography

In my study, I evaluated the effects of spatial and temporal variation in moisture availability on both the spatial and temporal variation in annual growth of yellow-poplar. This thesis has two main objectives. The first objective was to evaluate whether there has been any significant long-term increases or decreases in annual growth of yellow-poplar. I defined "long-term" changes in growth as trends in growth that lasted for a decade or

longer. What were the initiation time, the extent, and any probable causal factors of these trends in growth? One hypothesis concerned the occurance of a decline in growth beginning in the mid-1980's. Was this a significant long-term decline and was climate or specifically drought the probable causal factor of the decline?

The second objective was to determine how temporal and spatial variation in yellow-poplar growth was affected by temporal and spatial variation in moisture availability. How did topographic position affect mean annual growth and variation in annual growth across a long history of climatic conditions? How did topographic position affect mean annual growth and variation in annual growth given specific climatic conditions such as drought or wetness?

There are two hypotheses associated with the second objective. First, was mean annual growth for yellow-poplar higher on mesic locations than mean annual growth on xeric locations? Second, was variation in mean annual growth for yellow-poplar lower on mesic locations than on xeric locations? This presumed that annual growth would become more variable as topography limited the moisture available at a site, therefore increasing the influence of year-to-year climate variation on growth variation (Fritts 1976; Fritts and Swetnam 1989).

CHAPTER II

LITERATURE REVIEW

Factors that Influence Yellow-Poplar Growth

In this section, I discuss studies that describe the relationship between yellow-poplar and its environment. There are many studies over a wide range of topics that provide some understanding of the dynamics between yellow-poplar growth and associated climate and site factors.

Olson (1969) presented the findings of many studies throughout the eastern United States. These studies found that rainfall distributed over the growing season and adequate rainfall early in the season had a significant effect on radial growth. Site index was found to be related to soil depth, soil moisture, and topographic position (coves are best and ridges are worst). Another study in New Jersey found that topographic position, depth of soil, and soil drainage were highly related to site index (Phillips 1966).

A study in the Central States related yellow-poplar and oak growth, and found that yellow-poplar outcompetes oaks (*Quercus* spp.) on good and moderate sites, but would not compete as well on poor sites (Carmine and Kahn 1983). Oaks can outcompete yellow-poplar on poor sites such as ridge tops.

A study on soil-plant water relationships on the Oak Ridge Reservation, TN modeled yellow-poplar evapotranspiration rates as related to soil depth, root depth, and

precipitation inputs (Luxmoore et al. 1978). This study suggested that "soil-plant water relations may have a large effect on growth of these trees and even in moist sites growth may be periodically limited by water supply."

A simulation model was developed for a beech-yellow-poplar stand on the Oak Ridge Reservation to explain the effect of environmental gradients on the stand (Shugart et al. 1979). In this study, increasing mean annual temperature was correlated with decreases in yellow-poplar biomass. The decrease in biomass was probably due to increases in drought stress associated with higher temperatures.

McNab (1993) studied the effects of landform on yellow-poplar site index in the Blue Ridge Physiographic Province. Three variables (landform index, terrain shape index, and cosine of aspect) explained 31% of variation in site index.

McNab (1989) related terrain shape index (curvature of land surface) to yellow-poplar site index in the Southern Appalachians and found that terrain shape index explained 51% of site index variation. Quantifying the measurement of fine scale topographic changes with an index of landform is an improvement over simply observing locations and then making subjective judgements that lump locations into a few broad topographic categories such as ridge, slope, or valley

Tree-Ring Analysis

In this section, I discuss the use of tree-ring analysis to measure relationships between radial growth of stems, and climate and site data. First, I present the general

principles of tree-ring analysis and then I discuss some specific cases that used tree-ring analysis to determine growth response to given variables.

Tree-ring analysis procedures

Several sources explain tree-ring dating and analysis procedures. Step-by-step procedures for collecting increment cores, preparing them for crossdating and measurement, crossdating cores, and measuring ring widths are given by Stokes and Smiley (1968).

Crossdating is a procedure in which the year associated with each annual ring is identified and then verified. On an increment core there is a sequence of ring widths that can be identified (i.e. wide ring, wide ring, narrow ring, medium ring, narrow ring, wide ring, etc.). The sequence in the above example would correspond to: wet year, wet year, dry year, normal year, dry year, wet year, etc. The sequencing and widths of rings will be very similar for all increment cores taken from a particular species at a study site. The presence of the ring sequences allows the year assigned to a specific annual ring to be accurately identified in all of the increment cores. The dating of the cores can be verified with a climate record for the region of the study site to assure that the ring sequences correspond to climatic events. Crossdating also helps identify the presence of missing rings and false rings. If an expected ring is missing from a sequence then a missing ring has been identified and similarly if an unknown ring appears in a sequence then a false ring has been identified. After the tree-ring cores are dated, the widths can be measured. The tree-ring measurements can then be analyzed with a tree-ring dating quality control program to verify that the dating is accurate.

The computer program COFECHA, a tree-ring quality control utility, can be used to statistically analyze crossdated tree-ring measurements and determine if there are any measurement or crossdating errors that need to be corrected (Holmes 1983). Once crossdated measurements have been obtained and checked for errors, those measurements are then ready for standardization.

Cook (1985) describes the uses and methods of the computer program ARSTAN for standardizing the series of measurements from each tree. Standardization is a procedure where variance associated with undesirable growth trends in each individual tree-ring series is removed. ARSTAN fits linear lines, exponential curves, or cubic smoothing splines to tree-ring data to remove age-related growth trends as well as other undesirable growth trends that make direct comparison between ring series difficult. ARSTAN is a program that "whitens" the variance of each individual tree-ring series so that the individual tree data can be used for analysis or averaged into mean chronologies (mean time series) for analysis.

Fritts (1976) discusses multiple linear and multivariate regression procedures which can be used for determining relationships between mean time series and climate data. VanDeusen (1989) explains a step-by-step approach to tree-ring analysis and Jacoby and Cook (1981) discuss the use of principal components analysis (PCA) to relate tree-ring mean time series with climate data.

Converting tree-ring measurements in a series to basal area increments (BAI's) is a standardization technique for removing long-term trends due to increasing stem circumference as a tree ages. BAI's are an alternative to the use of ring width indexes (RWI's) which are ratios produced in standardization techniques used by

dendrochronologists using software such as ARSTAN. Visser (1995) describes various procedures for calculating BAI's from tree-ring widths. Bark width, ring width, and tree diameter is used to estimate the area or BAI for each year of growth in a ring series. BAI data can be used for building chronologies and in statistical analysis, using the same methods based on RWI data.

Cases using tree-ring analysis

Kolb and McCormick (1993) studied the decline of sugar maple (*Acer saccharum*) in Pennsylvania using patterns of BAI. They discovered that defoliations and droughts during the 1960's and 1970's caused a decline in BAI in sugar maple.

Tainter et al. (1990) used BAI to determine an association between short-term changes in climate and radial growth of red oak species. Short-term droughts caused a decline in radial growth, but did not cause any long term effects on radial growth. A series of accumulating short-term droughts caused a marked decline in radial growth and tree health. Short-term droughts had a greater effect on radial growth following the series of accumulating droughts than did droughts before the long series occurred.

Abrams, Ruffner, and Morgan (1998) studied the effects of drought on tree-ring growth for ten hardwood species across a range of sites in the Ridge and Valley Province of central Pennsylvania. They looked at the effects of drought on trees that were growing in wet-mesic, mesic, dry-mesic, and xeric sites. They noted that different species responded with varying amounts of growth reduction across the range of sites. They found that trees in general suffered the greatest declines in growth on wet-mesic and xeric sites and the trees that suffered the smallest declines were found in the intermediate mesic

areas. They found that the species showing the greatest declines were red maple *(A. rubrum*) in valleys, black cherry (*Prunus serotina*) in the barrens and riparian sites, and red oak (*Q. rubra*) and red maple on the ridges.

Liu and Muller (1993) studied the effect of drought and frost on radial growth of hardwood trees in Kentucky. Trees in the dominant and codominant crown classes showed a greater reduction in radial growth due to drought and frost than did trees in the understory.

Orwig and Abrams (1994) studied the influence of species tolerance on radial growth. Yellow-poplar had greater radial growth than blackgum (*Nyssa sylvatica*) due to its dominant canopy position. Blackgum demonstrated less radial growth because of its suppressed position in the canopy, but growth increased when blackgum was released.

Yin and Arp (1994) studied sugar maple to determine the influence of climate and soil factors. When only climate data was considered 63% of variation in radial growth could be explained. When soil data were added about 83% of variation in radial growth could be explained.

A doctoral study by Smith (1990) on four hardwood species at sites across Tennessee related climate to radial growth. Radial growth showed a decrease in sensitivity to climate over time. Sensitivity to climate may decline as a result of increasing stand age.

CHAPTER III

METHODS

Study Area

Walker Branch Watershed (WBW) (Figure 1) is located on the Department of Energy's Oak Ridge Reservation near Oak Ridge, Tennessee. The area was occupied by farms and homesteads with patches of woodland prior to the creation of the Oak Ridge Reservation in 1942; however it has become completely forested and relatively undisturbed (Johnson and Todd 1990). WBW is a 97.5-ha forested watershed (Johnson and Todd 1990) that lies in the Ridge and Valley Physiographic Province of east Tennessee. Elevation ranges from 265 m at the lowest point where Walker Branch exits the watershed to 350 m at the crest of Chestnut Ridge (Huston and Fontaine 1994). The watershed is characterized by a humid climate with a mean annual rainfall of 140 cm, and a mean annual temperature of 14.5°C (Garten, Huston, and Thoms 1994). On the ridges and slopes the soils are primarily ultisols, well drained, very high in chert, low pH, and low base saturation (Lietzke 1994). The valley floor is comprised primarily of soils formed in modern alluvium (Lietzke 1994). The oak-hickory forest cover type is predominant with scattered pine on the ridges and mixed hardwoods in the valleys (Huston and Fontaine 1994).

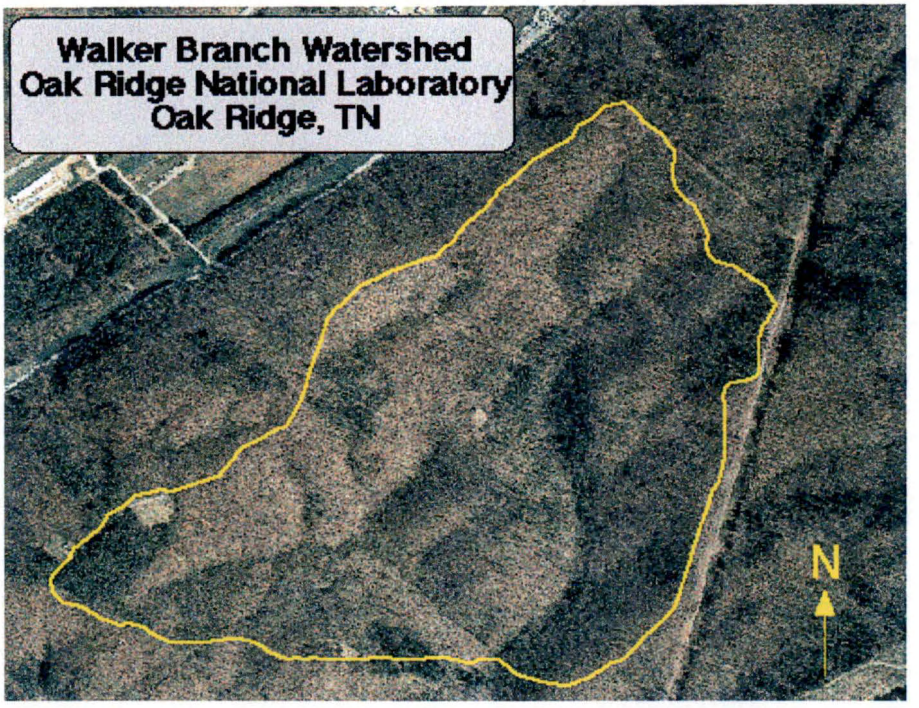


Figure 1. Aerial photograph of Walker Branch Watershed. Photograph shows the boundaries of the 97.5-ha watershed located near Oak Ridge Tennessee.

Data Collection

An extensive collection of site and climate data was available for use in this research. Much of the site data that was obtained was taken from a geographic information system (GIS) of Walker Branch Watershed. In addition to the data that were already available, tree ring data and supplementary stand characteristic data were collected.

Sample Size and Selection

An established grid system has a southwest to northeast orientation on WBW with grid stations at line intersections that are approximately 80 m apart. To keep the sample

size manageable only every other southwest to northeast line was sampled which reduced the number of grid stations available for sampling to 80 of the 156 grid stations. The southwest to northeast grid lines were used because they give a better representation of the changes in topography than do the southeast to northwest grid lines. Also, any grid station located near or in a clearing, roadway, or research project location was rejected for sampling because those sites were associated with recent or ongoing anthroprogenic disturbances which may have altered the growth rates of trees growing on or near those sites.

At each grid station, only dominant or codominant yellow-poplar trees with minimum diameters of 30 cm were sampled. No more than three trees were selected at each grid station. Only those trees located within about 20 m of a grid station were sampled. Of the 80 grid stations visited, only 46 stations had yellow-poplars that met the criteria for sampling. There are 106 trees in total that were sampled from WBW.

Collection of Site, Tree and Stand Data

Data collected from each tree consisted of diameter at breast height (DBH), crown position and vigor, neighborhood basal area to assess levels of competition associated with each tree, and two increment cores.

At each grid station, total basal area and yellow-poplar basal area were collected with a 2.5 m^2/ha prism to give an indication of competitive stress affecting each sampled yellow-poplar tree. The percent of total basal area attributed to basal area from yellow-poplar was calculated at each location to identify whether there was an inter-species or intra-species association affecting annual growth rates. The topographic position was

also noted for each grid station. Each grid station was classified as being located on a ridge, southwest facing slope, northeast facing slope, or valley floor. The four categories were ranked in order of increasing moisture based on exposure to solar radiation determined by aspect.

The distance and direction to each sample tree from the grid station was also noted. Each tree location was labeled according to the identification number of the neighboring grid station. The distance and direction of each tree from the grid station and the grid station identification number were used to extract data from the Walker Branch Watershed GIS. The data extracted from the GIS were used to calculate topographic index and to describe land-use history, and soil classification.

The topographic index, $\ln(\alpha/\tan\beta)$, measures potential moisture availability of a site based on characteristics of the topography where the site is located (Bevin and Wood 1983). The topographic index of a site is calculated by taking the natural logarithm of the ratio of upslope drainage area per unit contour length (α) to the slope angle of the site ($\tan\beta$). Figure 2 shows the distribution of topographic index values across WBW. Topographic index values can range from as low as 3.5 to as high as 15.0 on WBW. The most xeric location where a tree was sampled has a topographic index value of 5.32 and the most mesic location has a value of 14.46. The median value for sampled yellow-poplar locations is 6.91.

Land-use history was used to classify trees according to any disturbance that may have altered the suitability of a site to the presence and annual growth of yellow-poplar. Figure 3 shows land-use classifications across WBW. There are two major categories of land-use. The first category includes forest stands that show no evidence of major

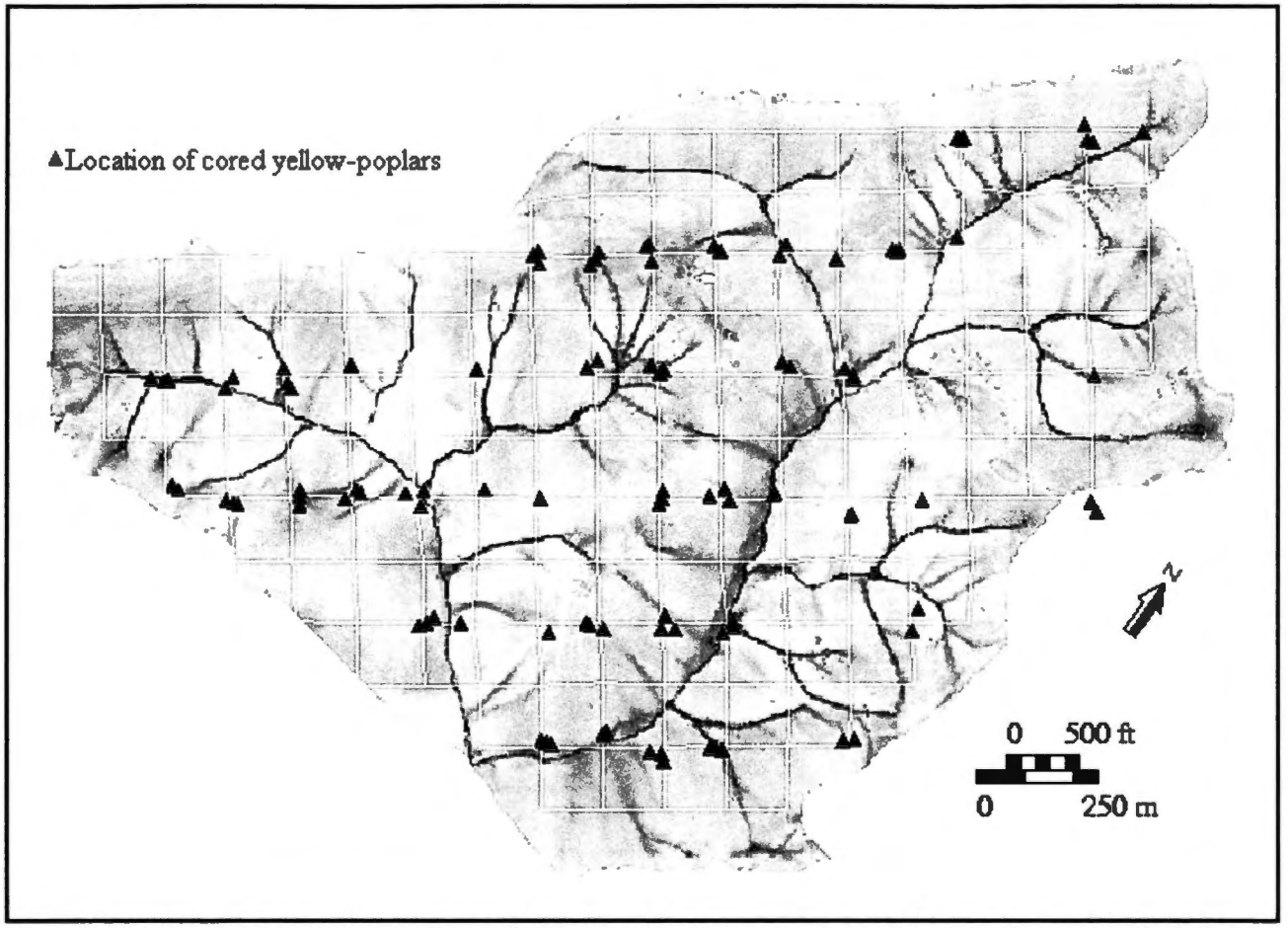


Figure 2. Topographic index, ln (α/tanβ), map of Walker Branch Watershed. Topographic index is the natural logarithm of the ratio of upslope drainage area per unit contour length (α) to the slope angle of the site (tan β). Moisture level increases as shading darkens.

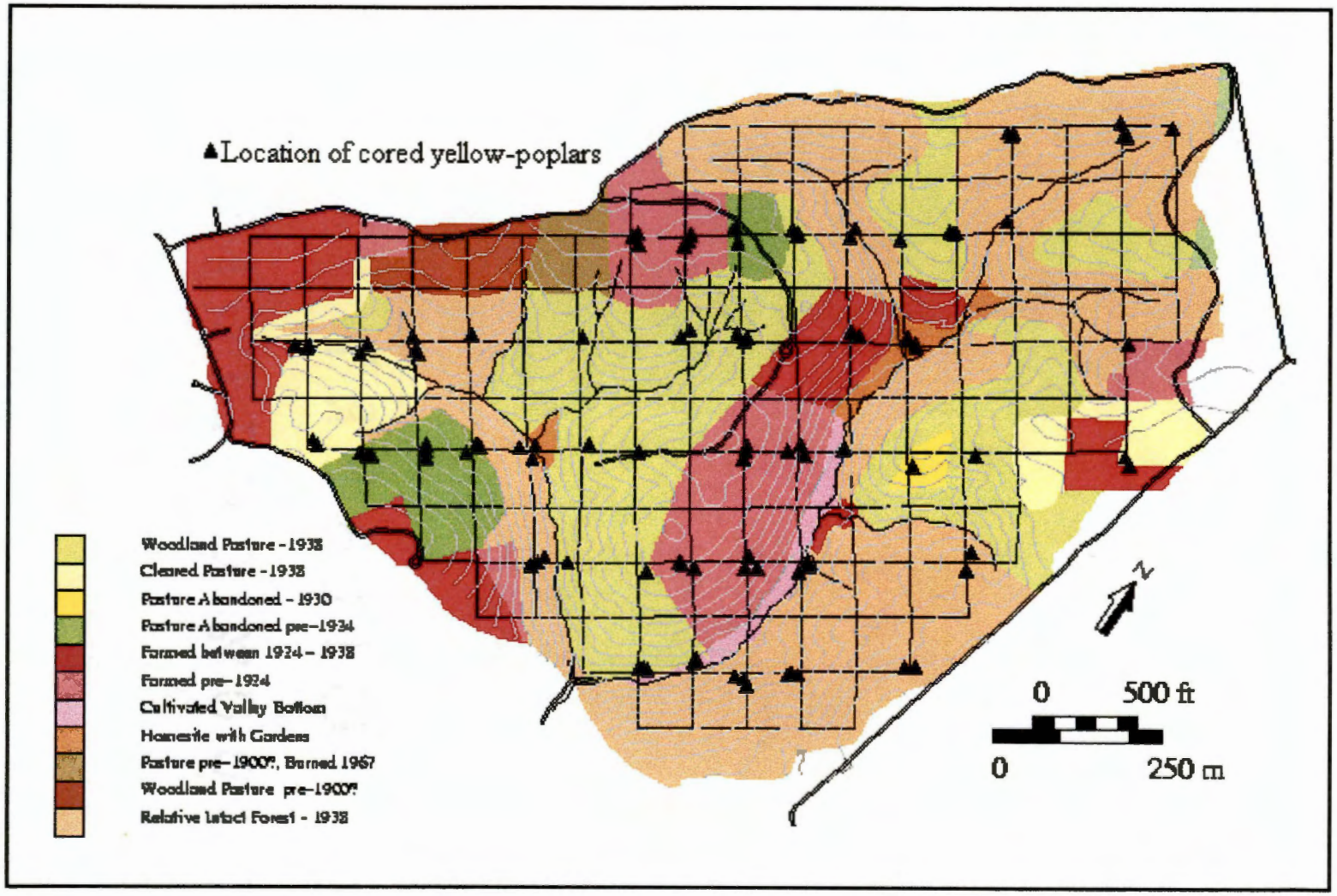


Figure 3. Land-use history map of Walker Branch Watershed.

anthroprogenic clearing activity. The second major category includes forest stands that reclaimed eroded fields abandoned in 1937 and fields that were abandoned in 1942 after the area was acquired for the Manhattan Project. These fields were in various types of cultivation and pasture, but they all fit in the broad category of having been cleared of forest vegetation for agriculture and then abandoned around 1940.

Soils at each site were classified so that patterns in yellow-poplar distribution and growth could be associated with soil type. Four very broad and general soil classifications were used: residuum found on ridgetops, colluvial soils found on slopes, modern alluvium deposited in valleys, and ancient alluvium which is found on ridgetops. Figure 4 shows the distribution of the soil types on Walker Branch Watershed.

Climate Data

I used several categories of climate data in my analysis. I obtained monthly Palmer Drought Severity Index (PDSI) values for Tennessee Climate Division 1 (NOAA 1999). I obtained descriptions of PDSI classifications (Table A-1) to help identify which PDSI values corresponded to specific climatic conditions ranging in categories from severe drought to extreme wetness (National Drought Mitigation Center 1999). Total monthly precipitation and mean median monthly temperature values for WBW were also obtained for the time period from 1951 through 1997.

Increment Core Collection, Preparation, and Measurement

The increment cores were collected between April and August 1998 using the methods described by Stokes and Smiley (1968). Two increment cores were collected at

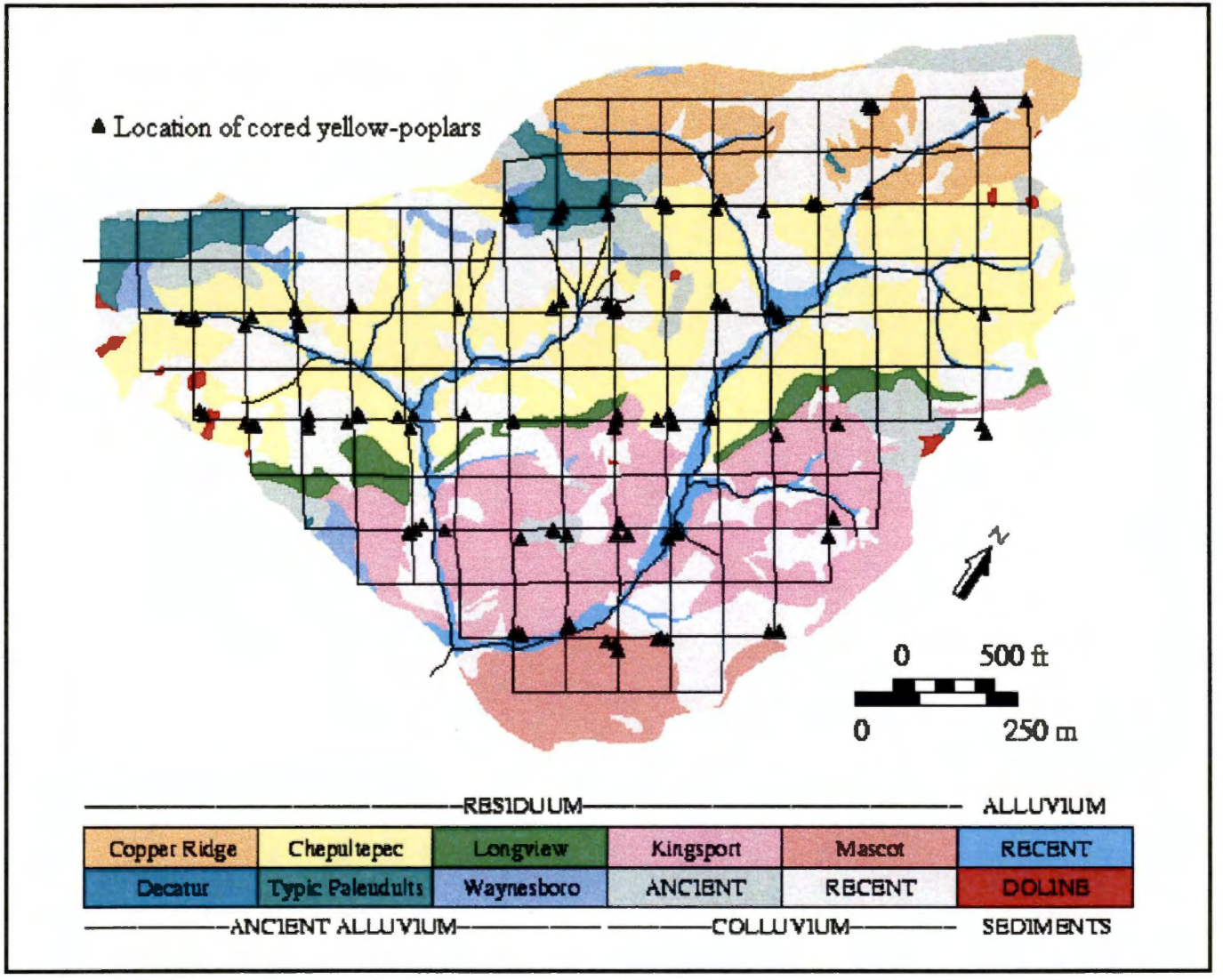


Figure 4. Soils map of Walker Branch Watershed.

breast height (1.3 m) from each tree. The cores from each tree were taken 180 degrees apart and parallel to the contours of the land to reduce the influence of wood stress on ring width associated with slope. Each core was placed in a plastic drinking straw, the ends of the straw were taped shut, and each core was labeled according to its donor tree identification and neighboring grid station. The cores were then stored in a dry place to inhibit the growth of molds.

After all the trees were sampled, the increment cores were oven dried for 24 hours in a home oven at the lowest temperature setting and then glued into slots in thin strips of wood. Mounting the cores in wood strips was necessary so that the cores could be surfaced. Surfacing was done by sanding the surface of the mounted cores using a belt sander with progressively finer grades of sandpaper until the annual rings in each core could be easily and clearly seen (Stokes and Smiley 1968).

After the cores were mounted and sanded, the rings were crossdated according to standard dendrochronological techniques described by Stokes and Smiley (1968). Crossdating of tree-ring cores involved the development of skeleton plots on a small sample of increment cores. After the skeleton plots were made, they were compiled into a master chronology through a method of averaging the individual plots into one master plot. The specific year associated with each tree-ring in a core could be identified by examining each mounted core under a microscope and making comparisons between the core and the master chronology. The crossdating procedure identified where missing rings and false rings were located as well as determining the exact year for each tree-ring of an increment core.

The ring widths of the crossdated cores were then measured using a Velmex measuring table with a microscope and a fiber optic light source. A tree-ring data management computer program, METRONICS, was used to record and store the tree-ring width data from the measuring table. The data for each core were stored in time series format according to the identification number of the increment core.

After all the increment cores were measured, the computer program COFECHA, was used to identify any possible measurement and crossdating errors (Holmes 1983). If potential errors flagged by COFECHA could be verified by re-examination of flagged cores, the appropriate measurement or crossdating correction was made. Any potential errors flagged by COFECHA that could not be verified as true errors were ignored.

The end result of the crossdating, measuring, and COFECHA quality control was a dated and measured set of tree-ring data that should be error free. The data consisted of dated ring-width measurements in time series format for each individual increment core and were ready for standardization and data analysis.

Standardization is usually performed by fitting linear or negative exponential regressions to each time series to remove variance associated with age. Commonly, a computer program, such as ARSTAN (Cook 1985), is used to remove undesirable trends from each time series. However, I converted ring width measurements to basal area increments (BAI's) as a method of standardization through procedures described by Visser (1995) and by Kolb and McCormick (1993). The use of BAI's removed the variation in radial growth caused by increasing stem circumference as a tree ages (Kolb and McCormick 1993). The formula for obtaining BAI as described by Kolb and

McCormick was

$$BAI = \pi(R_n^2 - R_{n-1}^2)$$

where R is stem radius and n is year. The two BAI time series for each increment core from a tree were then averaged to produce a mean BAI time series for each tree. This averaged variation in growth from both cored locations of the tree, creating a better representation of how the BAI of an individual tree varies (Fritts 1976).

Data Analysis

In this section, I describe the general procedures used to perform the data analysis. Data analysis used both graphical representations and statistical testing of the data to determine temporal and spatial patterns in BAI of yellow-poplar on WBW. There are two methods by which BAI data from each tree were organized for statistical analysis.

In the first data organization method, temporally distributed data were used for analysis of temporal variation in BAI. Individual tree-level BAI time series were averaged into mean BAI time series or group-level time series; the mean time series were used as dependent variables and continuous temporal variables such as monthly climate data were used as predictor variables.

I began the temporal analysis by making a time series plot of the WBW BAI time series (mean BAI for all sampled trees on WBW) and a plot showing the BAI time series for trees grouped into mesic, intermediate, and xeric topographic categories to examine

temporal patterns in growth within broad spatial categories. I examined the time series plots to identify long-term increases and decreases in growth.

Using an autoregressive modeling function contained in the ITRDB Program Library software (Grissino-Mayer, Holmes, and Fritts 1997), variance associated with serial correlation in the time series was removed and residuals were produced for graphical analysis. Using response function analysis (Fritts 1976), variance associated with climate variables was removed and another set of residuals for additional graphical analysis was produced. I used this graphical analysis in conjunction with paired t-tests to identify significant long term changes in BAI and to make determinations of the causal factors associated with those long term changes.

In addition to the analysis to find growth trends, I also performed a response function analysis of BAI time series to determine the overall effect of climate on BAI time series that are grouped by either site or stand characteristics. In the response function analysis, I used mean BAI time series based on the overall (WBW Overall) population and for two subpopulations of trees that differed significantly in age. The two subpopulations corresponded to the two levels of land-use that were identified. There were older trees (WBW Old) that were already present when the Oak Ridge Reservation was established and younger trees (WBW Young) that colonized abandoned fields after the Reservation was established. I compared the two subpopulations to each other and to the overall population. I also used mean BAI time series where trees were grouped into categories determined by the spatial distribution of moisture availability, such as mesic or xeric topographic locations. For each population category (the WBW Overall population and the two subpopulations), I performed three response function analyses. These

analyses include one response function analysis based on the mean BAI series for all trees in that category and two more for the mesic and xeric subgroups within that category. There are three population categories (WBW Overall, WBW Old, and WBW Young) and two primary subdivisions (Mesic and Xeric) within each population category. There is also an intermediate subdivision (WBW Intermediate), which was used in some analyses.

In response function analysis, there are predictor variables based on monthly or seasonal climate averages that are used to predict the "response" of BAI or some other measure of annual growth such as ring width index. Median monthly temperature and total monthly precipitation for fourteen months are commonly used as predictors in response function analysis. I used the months July from the previous growing season through August of the growing season where the BAI response occurs. Backwards-stepwise regression procedures were used to select which months significantly explain variance in the response of BAI. After regression models were selected, model R^2 for each group was compared and climate predictor variables selected for each group were examined to determine how climate effects the temporal BAI of each group.

In the second data organization method, spatially distributed BAI data from individual trees were used as the dependent variables, and stand and site characteristics were used as predictor variables or classification variables.

I used time series plots of BAI, PDSI, and total monthly precipitation to identify distinct periods of time in BAI that appeared to be associated with climatic changes affecting moisture availability. For each time period, I calculated mean BAI and coefficient of variation (CV) of BAI for each tree. I also calculated mean BAI and CV

BAI for the entire BAI series for each tree. Values of mean BAI and CV for the whole range of measured growth for each tree and values of mean BAI and CV for smaller time periods of the overall range of growth for each tree were used as indicators of change in BAI response. I used two schemes for categorizing the measures of mean BAI and CV. Both schemes provided insight into how BAI varies spatially within temporal categories.

The first scheme consisted of using groups or subsamples of the overall sample of yellow-poplars to make comparisons. Individual tree data were categorized or grouped according to broad classifications of potential moisture availability such as trees on mesic sites versus trees on xeric sites. The BAI and CV data were used as dependent variables and potential moisture availability (mesic or xeric categories) was used as a classification variable for ANOVA (Analysis of Variance) procedures.

I determined whether a tree location was generally mesic or generally xeric by examining the distribution of tree locations and their associated topographic index, ln ($\alpha/\tan\beta$), values. I examined where the first quartile, median, and third quartile was located in the distribution of topographic index and designated trees below the first quartile as xeric and trees above the third quartile as mesic. Trees between the first and third quartile were generally considered to be near the median topographic index and were classified as intermediate in potential moisture availability.

The second scheme focused on using the fine-scale distribution of tree locations by topographic index instead of grouping trees into broad categories. I was interested in the potential moisture availability at each tree location across the entire range of topographic index values rather than the potential moisture availability for broad classifications of trees. The BAI and CV data were used as dependent variables, and

stand and site data were used as predictor variables for regression analysis. Specifically, backwards-stepwise regression was used to select which stand and site characteristics best explained variance in BAI.

For the regression analysis, it was necessary to rank the categorical data. The use of categorical data such as soil classes would have been meaningless, but the categorical data were ranked according to BAI statistics so they could be used as predictor variables in regression analysis. I examined mean BAI, median BAI, variance and other statistics (Table A-9) for each soil class and determined that the classes could be ranked according to their effect on BAI. The four soil classes residuum, colluvium, ancient alluvium, and modern alluvium were ranked by mean BAI. Trees on residuum had the lowest mean BAI and were assigned a ranking of 1. Trees on colluvium had the second lowest mean BAI and were assigned a rank of 2. Trees on modern alluvium had the second highest mean BAI and were assigned a rank of 3. Trees on ancient alluvium had the highest mean BAI and were assigned a rank of 4.

I also examined statistics for the land-use classes. There are only two levels of land-use so ranking was not necessary, but I assigned a rank of 1 to the class of older trees because they had a lower mean BAI than the younger trees which were assigned a rank of 2.

For all statistical tests, the level of significance was held at 95% or α=0.05. Using ANOVA, groups were significantly different if the null hypothesis was rejected at α=0.05. For all regression analysis, predictors were only included in models if they significantly reduced SSE (sum of squared errors) at α=0.05.

All statistical analyses including ANOVA, regression, correlation, and t-tests were performed with SAS (1998). For every statistical test, underlying assumptions that validate the use of that test had to be met. Parametric procedures require independence within and between groups, normal distributions, and homogeneity of variance among groups. There were instances where a log (10) transform of the BAI data was required to produce distributions that were approximately Gaussian in shape. In some analyses, I used nonparametric procedures based on rank transforms of the BAI data (Conover 1999; Conover and Iman 1981). For any tests where the underlying statistical assumptions were violated, remedial measures were used.

CHAPTER IV

RESULTS

The results for each objective of this research project are presented in separate sections. I present results that are specific to the questions and hypotheses associated with each objective. Some of the results presented for the first objective helped guide the direction and development of the analysis associated with the second objective.

Objective 1

Objective 1 was to evaluate whether there have been any significant long-term increases or decreases in yellow-poplar growth and to determine what was the initiation time, the extent, and any probable causal factors of these trends in growth. In this section, I present results that are relevant to answering these questions for observed growth trends and, more specifically, to test the hypothesis that there was a significant decline beginning in the mid-1980's that was initiated by drought stress.

Were there any significant long-term changes in growth? A time series plot of mean BAI for all WBW trees (Figure 5) shows that there are some very strong long-term trends present in BAI for yellow-poplar at the watershed scale. I defined "long-term" changes in growth as changes that were not associated with year-to-year variations

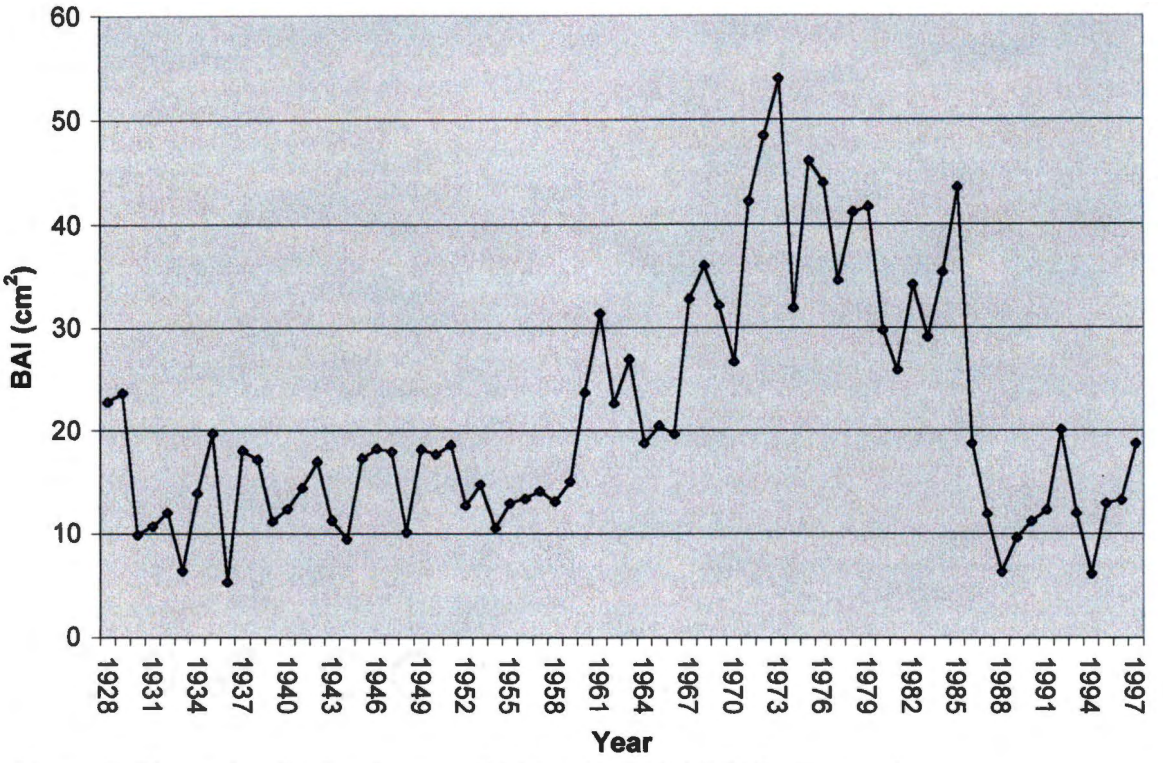


Figure 5. Time series plot showing mean BAI for all sampled WBW yellow-poplars.

in growth, but rather were indicative of trends that lasted longer than many subsequent years. There were two major departures from average BAI that were present in the BAI time series for WBW. The first major change in growth was a very large increase in BAI that began in 1961, built to a peak in 1973, and ended in 1985. The second major departure in growth began with a very sharp decline in BAI in 1986 and very low levels of BAI expressed throughout the remainder of the measured time series, which ended in 1997.

I used paired t-tests to determine the significance of these two departures in growth. I compared the mean BAI of each tree for the 1961 to 1985 time period with mean BAI prior to 1961. Mean BAI from 1961 to 1985 for WBW yellow-poplars was significantly greater than mean BAI prior to 1961. The hypothesis that there would be no

difference in BAI was rejected at alpha = 0.05 with a t statistic = -18.145 with a p-value = <0.0001. I also tested the hypothesis that there would be no difference between mean BAI for the 1986-1997 time period and mean BAI prior to 1986. The hypothesis was rejected with a t statistic = 14.439 with a p-value = <0.0001.

I also ran a paired t-test using mean BAI from the period before 1961, excluding the 1961to 1985 period, to help determine the significance of the 1986 to 1997 decline. This earlier period may be more indicative of "normal" yellow-poplar growth rates because it excludes the long-term trend of very high BAI between 1961 and 1985. I tested for a difference between mean BAI prior to 1961 and mean BAI between 1986 and 1997. This test yielded a t statistic = 2.541 with a p-value = 0.0127. Using the more stringent criteria of excluding the period of very high growth as "normal" growth, the paired t-test results were significant.

Figure 6 shows mean BAI for trees in mesic, xeric, and intermediate categories based on topographic index (ln (α/ tan β)) values. An examination of Figure 6 shows that the growth trends which were identified for all WBW trees are also present in all categories based on topographic index These growth trends occurred across WBW regardless of spatial differences in moisture availability at each yellow-poplar's location.

What was the cause of each of the two long-term changes in growth? The changes in growth were occurring across all of WBW regardless of topographic index, which indicates there may be a climatic link. To identify a climatic association I performed a response function analysis (Fritts 1976) to determine the relationship between BAI and monthly climate variables. I used backwards-stepwise regression to

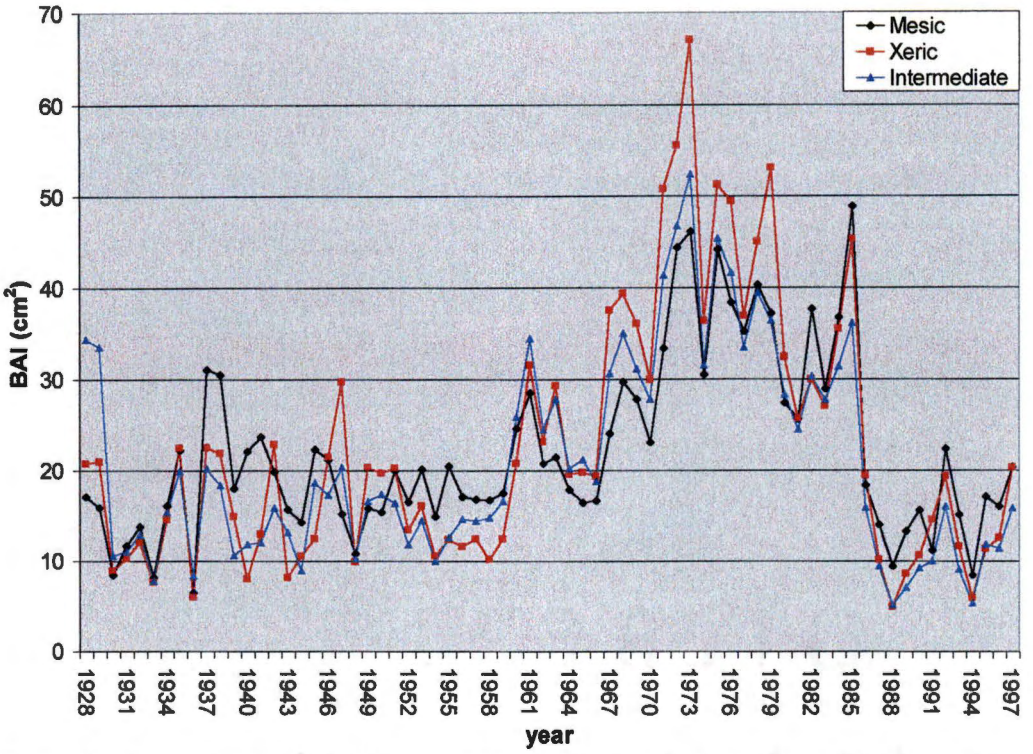


Figure 6. Time series plot showing mean BAI for yellow-poplar trees grouped in topographic index categories.

select which of the monthly temperature averages and monthly precipitation totals significantly removed variance in BAI. I determined the response function for the mean time series for all WBW trees and for the mean time series based on the topographic index categories. I discovered that there was a significant amount of first-order autocorrelation which needed to be removed from each of the mean BAI time series in the response function analysis. Using Spearman's Rho, it was found that the first-order autocorreclation of the WBW Overall mean time series was r = .81 with a p-value = <.0001.

Likewise, all of the other mean BAI time series by topographic index categories had similar levels of autocorrelation. I removed the autocorrelation by regressing BAI for year *t*

by BAI for year *t-1* (Fritts 1976). I included variables of BAI for year *t-2* through *t-n* (Fritts 1976) using backward stepwise selection, but none of these variables removed a significant amount of variance in BAI for year *t* and thus were excluded from the models. I then used the residuals from the autoregressive modeling as the dependent variable and used backward-stepwise regression to select monthly climate variables that significantly reduced variance in the residual time series. Figure 7 shows the residual time series variance associated with autoregression removed while Figure 8 shows the residual time series with variance associated with autoregression and climate removed. Removing variance in BAI associated with autoregression and climate greatly reduced the trends in growth that are apparent in Figure 6.

Examination of Figure 9 also reveals some graphical evidence of the link between climate and long-term changes in growth. Figure 9 shows WBW mean BAI versus median growing season PDSI values from 1928 to 1997. This graph shows that there were no major growing season droughts between 1961 and 1985 for NCDC Tennessee Climate Division 1, which covers the East Tennessee region. This is a time period where PDSI indicates a long-term wet climatic condition. Climate in association with the autoregressive properties of annual wood production provides an answer to what caused the increase in BAI between 1961 and 1985.

Examination of the PDSI values also provided insight into the cause of the drastic decline in growth that began in 1986. In 1985 a drought began that lasted through 1988 that is unequaled in intensity in the PDSI records for NCDC Tennessee Climate Division 1. The 1985 and 1987 the drought index values, which are lower than –2.0 are classified as

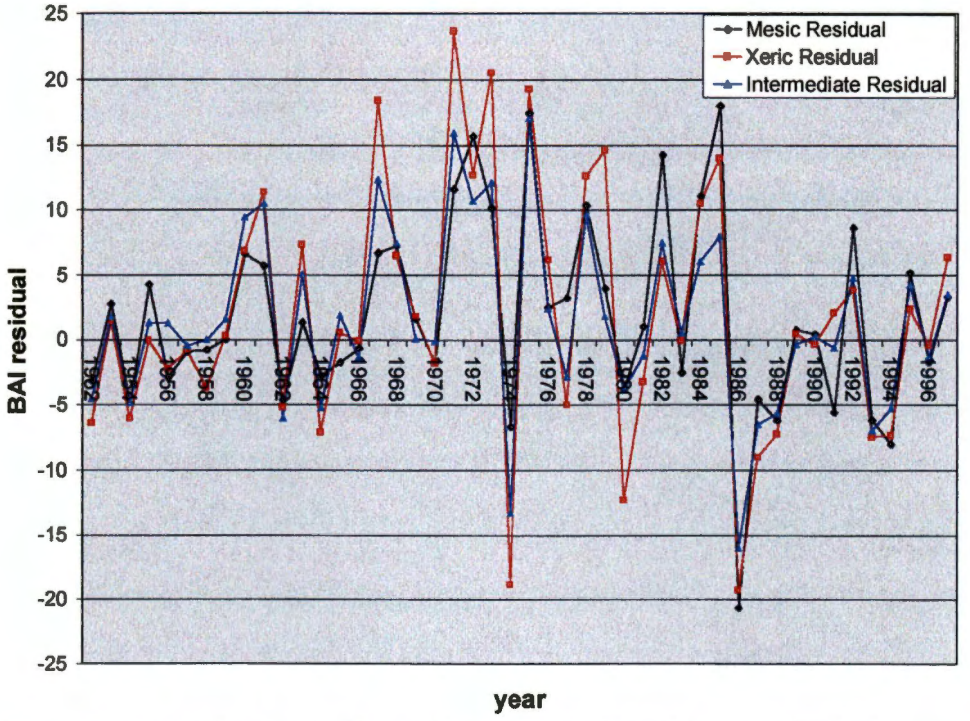


Figure 7. Time series plot showing residuals of BAI with variance associated with autoregression removed. Trees are grouped into topographic index categories.

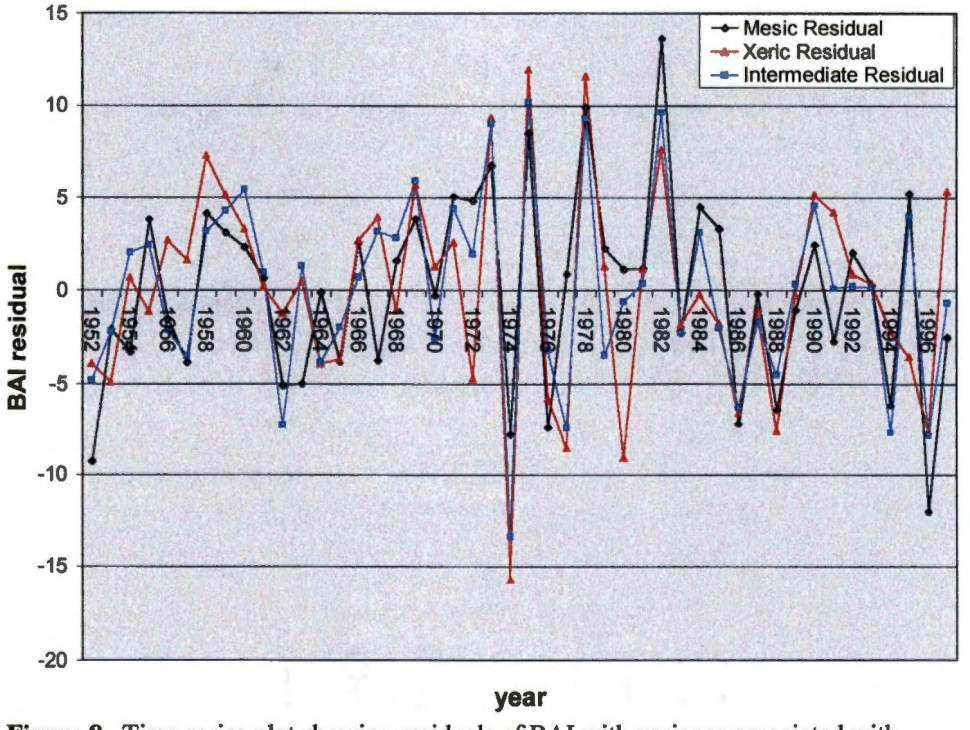


Figure 8. Time series plot showing residuals of BAI with variance associated with autoregression and climate removed. Trees are grouped into topographic index categories.

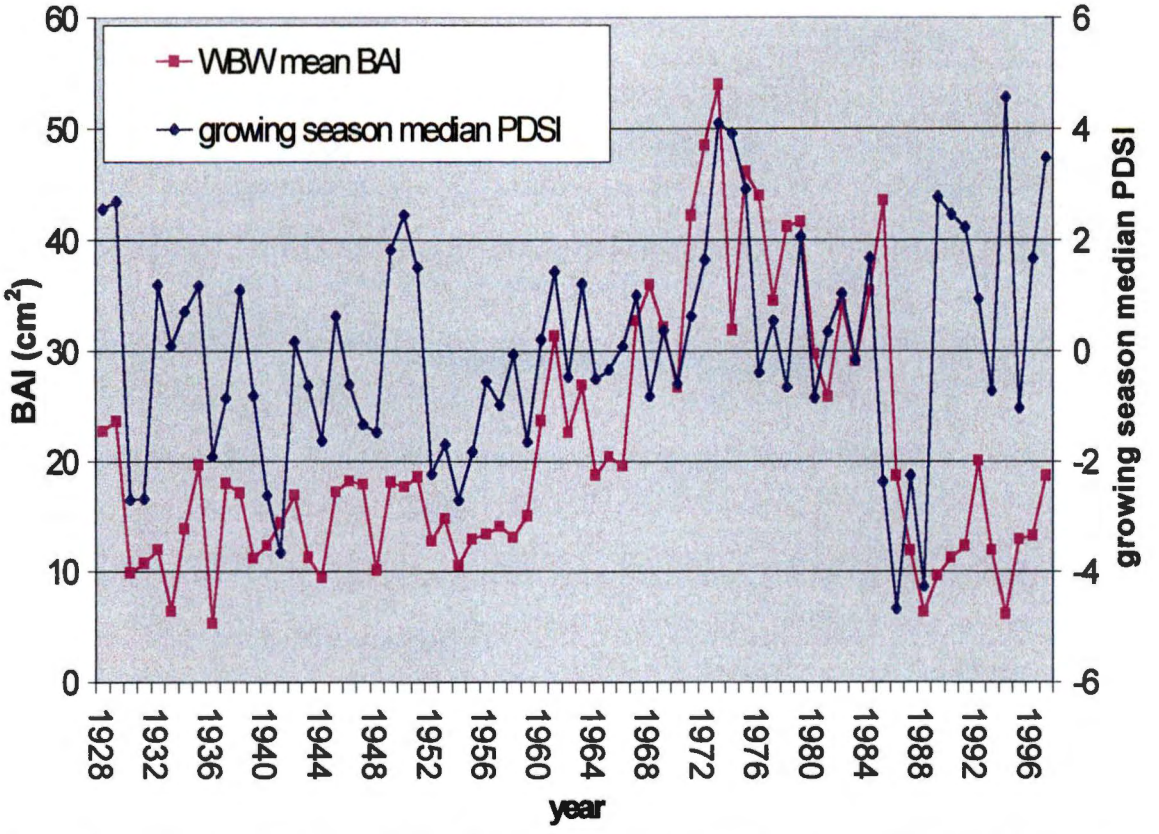


Figure 9. WBW mean BAI versus growing season median PDSI (April through August median PDSI). PDSI values are for NCDC Tennessee Climate Division 1 covering the East Tennessee region.

moderate, but the 1986 and 1988 the drought index values, which are lower than –4.0 are classified as extreme (Table A-1). This was a period of severe drought and was likely the cause of the abrupt decline in BAI that began in 1986 and lasted through the remainder of the measured time series. There were other major droughts in the climate record, but none that approached the level of extreme drought, which occurred in 1986 and 1988. It should be noted, that although climatic conditions improved between 1989 and 1997 there does not appear to be a significant recovery in BAI in response to the change in climatic conditions.

Objective 2

Objective 2 was to determine how temporal and spatial variation in yellow-poplar growth was affected by temporal and spatial variation in moisture availability. I was interested in how topographic position affected growth associated with long periods of general climate history and growth during specific climatic conditions such as drought or wetness. Results from ANOVA and multiple linear regression procedures are presented to provide explanation for two primary questions. How did topographic position affect annual growth across a long history of climatic conditions and how did topographic position affect annual growth given specific climatic conditions such as drought or wetness? Since there are two subpopulations within the population of WBW yellow-poplars, I present results that correspond to the 'WBW Overall' population, and the 'WBW Old' and 'WBW Young' subpopulations.

How did topographic position affect annual growth across a long history of climatic conditions?

Definition of 'Mesic' and 'Xeric' sites for the WBW Overall population was based on topographic index values. They were used to determine the effect of topography on the long-term pattern of BAI across a long period of climate history, using the extremes of the topographic index scale for WBW. I compared BAI of 18 trees located on mesic sites with that of 18 trees located on xeric sites. Only 18 trees were used in each group because I tried to use only trees that were near the extreme ends of the range of topographic index. Mean BAI and Coefficient of Variation of BAI (CV BAI)

were used as measures of growth and growth variability, respectively. ANOVA results showed that there is no significant difference between mean BAI in the mesic and xeric groups (F-Value of 0.01 with a p-value = 0.9260). The mean BAI for the Mesic group is 24.06 cm^2/year and the mean BAI for the Xeric group is 24.92 cm^2/year. It would seem, based on mean BAI, that there is little difference in growth between the wetter and drier locations. However, there was a highly significant difference in CV BAI between the Mesic and Xeric groups. Coefficient of Variation of BAI in the Xeric group was significantly greater than CV BAI in the mesic group (F Value = 27.47 with a p-value = <0.0001). The CV BAI for the Mesic group is 0.55 and the CV BAI for the Xeric group is 0.71. From 1997 to the beginning of each time series, year-to-year variation in BAI is significantly higher in the Xeric group than in the Mesic group.

I performed the same group of tests previously described, on the WBW Old and WBW Young subpopulations. For the WBW Old subpopulation, I used 20 trees from mesic locations and 20 trees from xeric locations to test for differences in group means with ANOVA. Mean BAI for the WBW Old/Mesic group is 21.67 cm^2/ year and mean BAI for the WBW Old/Xeric group is 19.90 cm^2/year. There was no significant difference between the group BAI means (F Value = 1.02 with a p-value = 0.3184).

Again there was a significant difference in CV BAI between the two groups (F Value = 18.62 with a p-value = 0.0001). CV BAI for the WBW Old/Mesic group is 0.58 and CV BAI for the WBW Old/Xeric group is 0.74.

For the WBW Young subpopulation, I used 10 trees from mesic locations and 10 trees from xeric locations to test for differences in group means using ANOVA. There

was no significant difference between the mean BAI for the WBW Young/Mesic group of 26.04 cm^2/ year and the mean BAI for the WBW Young/Xeric group of 31.66 cm^2/year (F Value = 1.62 with a p-value = 0.2200).

There was a significant difference in CV BAI between the two groups (F Value = 4.83 with a p-value = 0.0413). CV BAI for the WBW Young/Mesic group is 0.53 and CV BAI for the WBW Young/Xeric group is 0.62.

I also used the fine-scale distribution of yellow-poplar across the range of topographic index locations to determine the relationship between long-term changes in BAI across a long period of climate history. Mean BAI and CV BAI for each of the 106 trees in the WBW sample was used as the dependent variable in multiple linear regression. I used backward-stepwise regression to select which predictor variables significantly reduce variance in the dependent variable. I included topographic index, topographic location, soil class, percent yellow-poplar, land-use category, competing basal area, and crown vigor as predictor variables in the backward-stepwise selection process. Topographic index is the variable of most interest since it is a fine-scale continuous variable that estimates the potential moisture available at each tree location. Topographic location and soil class are similar variables that are correlated with moisture availability, but they are in broad categories rather than the fine-scale distribution of topographic index. For my analysis, the importance of the regression testing does not lie so much in developing regression models, but rather in demonstrating the inclusion or exclusion of the various variables.

Topographic index, soil class, and crown vigor were significant variables in the

multiple linear regression using mean BAI observations from the WBW Overall population. The last row of Table 1 shows the percent of variance explained by each significant variable, sign of the variables influence, and the model R^2 for the model using average BAI for all years as the dependent variable. These statistics indicate that for the measured segment of time (1928-1997), BAI was reduced as topographic index was increased. Crown vigor was an important variable that frequently was significant throughout the various regression analyses. In this model, trees with healthy crowns had higher BAI than trees with lower crown vigor.

Using CV BAI from 1928 to 1997 as the dependent variable, I performed another regression analysis on the WBW Overall population. Topographic index played a significant role in reducing CV BAI (last line of Table 2). Again, crown vigor was significant and shows that healthy crowns played a role in reducing CV BAI. I performed these same types of regression analyses using the WBW Old and WBW Young subpopulations (last lines of Tables 3 and 4). For the WBW Old subpopulation topographic index was not a significant variable influencing mean BAI over a long period of time. However, topographic index was very important in reducing CV BAI. Again, as crown vigor increased, mean BAI increased and CV BAI decreased. For the WBW Young subpopulation (Tables 5 and 6) average BAI decreases as topographic index increases while topographic index had no significant effect on CV BAI. There was a difference in how topographic index significantly affects BAI for the WBW Old and WBW Young subpopulations.

Table 1. Multiple linear regressions for the WBW Overall population using log(10) of the mean BAI for the specified time periods as the dependent variable. Significance of independent variables was determined using backward stepwise regression and alpha = .05 level significance for variable to remain.

Dependent Variable	Independent Variable														
	top. index		location		soil class		% yp		land-use		comp. BA		crown		
Time Period	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	model R^2
bai86-97 log			0.093	+									0.090	+	0.183
bai61-85 log	0.047	-			0.064	+							0.076	+	0.187
bai28-60 log	0.059	+							0.116	+					0.175
bai89-97 log			0.033	+									0.133	+	0.166
bai86-88 log			0.141	+							0.072	-			0.213
bai76-85 log	0.050	-									0.030	-	0.112	+	0.191
bai71-75 log	0.044	-			0.072	+							0.057	+	0.173
bai61-70 log	0.092	-			0.036	+	0.018	+					0.026	+	0.172
bai52-60 log	0.049	+							0.138	+					0.187
baiall log	0.041	-			0.070	+							0.157	+	0.267

Table 2. Multiple linear regressions for the WBW Overall population using log(10) of the coefficient of variation of BAI for the specified time periods as the dependent variable. Significance of independent variables was determined using backward stepwise regression and alpha = .05 level significance for variable to remain.

Dependent Variable	Independent Variable														
	top. index		location		soil class		% yp		land-use		comp. BA		crown		
Time Period	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	model R^2
cv86-97 log													0.095	-	0.095
cv61-85 log									0.051	-					0.051
cv28-60 log	0.045	-	0.079	+											0.124
cv89-97 log													0.062	-	0.062
cv86-88 log	0.100	-									0.068	+			0.168
cv76-85 log	0.042	-													0.042
cv71-75 log													0.051	-	0.051
cv61-70 log									0.045	-					0.045
cv52-60 log	0.034	-	0.107	+											0.142
cvall log	0.106	-							0.113	-			0.126	-	0.345

Table 3. Multiple linear regressions for the WBW Old subpopulation using log(10) of the mean BAI for the specified time periods as the dependent variable. Significance of independent variables was determined using backward stepwise regression and alpha = .05 level significance for variable to remain.

Dependent Variable	Independent Variable												
	top. index		location		soil class		% yp		comp. BA		crown		
Time Period	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	model R^2
bai86-97 log			0.053	+									0.053
bai61-85 log							0.095	+					0.095
bai28-60 log	0.094	+					0.121	+					0.215
bai89-97 log											0.056	+	0.056
bai86-88 log			0.109	+					0.072	-			0.181
bai76-85 log									0.055	-			0.055
bai71-75 log							0.102	+					0.102
bai61-70 log							0.088	+					0.088
bai52-60 log							0.155	+			0.049	+	0.204
baiall log							0.084	+			0.066	+	0.150

Table 4. Multiple linear regressions for the WBW Old subpopulations using log(10) of the coefficient of variation of BAI for the specified time periods as the dependent variable. Significance of independent variables was determined using backward stepwise regression and alpha = .05 level significance for variable to remain.

Dependent Variable	Independent Variable												
	top. index		location		soil class		% yp		comp. BA		crown		
Time Period	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	model R^2
cv86-97 log					0.062	-					0.066	-	0.129
cv61-85 log													0.000
cv28-60 log			0.087	+									0.087
cv89-97 log					0.056	-					0.062	-	0.118
cv86-88 log	0.062	-							0.101	+			0.163
cv76-85 log									0.063	+			0.063
cv71-75 log	0.085	-											0.085
cv61-70 log			0.071	-									0.071
cv52-60 log													0.000
cvall log	0.234	-									0.046	-	0.280

Table 5. Multiple linear regressions for the WBW Young subpopulation using log(10) of the mean BAI for the specified time periods as the dependent variable. Significance of independent variables was determined using backward stepwise regression and alpha = .05 level significance for variable to remain.

Dependent Variable	Independent Variable												
	top. index		location		soil class		% yp		comp. BA		crown		
Time Period	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	model R^2
bai86-97 log	0.108	-									0.338	+	**0.446**
bai61-85 log	0.220	-			0.103	+					0.036	+	**0.359**
bai40-60 log					0.117	+							**0.117**
bai89-97 log	0.104	-									0.317	+	**0.421**
bai86-88 log	0.258	-	0.250	+					0.035	-			**0.544**
bai76-85 log	0.125	-									0.203	+	**0.328**
bai71-75 log	0.225	-									0.028	+	**0.254**
bai61-70 log	0.217	-			0.111	+							**0.328**
bai52-60 log							0.279	+	0.121	-			**0.400**
baiall log	0.261	-			0.034	+					0.084	+	**0.378**

Table 6. Multiple linear regressions for the WBW Young subpopulation using log(10) of the coefficient of variation of BAI for the specifed time periods as the dependent variable. Significance of independent variables was determined using backward stepwise regression and alpha = .05 level significance for variable to remain.

Dependent Variable	Independent Variable												
	top. index		location		soil class		% yp		comp. BA		crown		
Time Period	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	partial R^2	sign	model R^2
cv86-97 log	0.090	+							0.216	+	0.092	-	**0.399**
cv61-85 log													**0.000**
cv40-60 log	0.328	-											**0.328**
cv89-97 log									0.176	+			**0.176**
cv86-88 log											0.467	-	**0.467**
cv76-85 log													**0.000**
cv71-75 log					0.028	-	0.225	+					**0.253**
cv61-70 log													**0.000**
cv52-60 log	0.602	-	0.052	+									**0.654**
cvall log											0.302	-	**0.302**

How did topographic position affect annual growth given specific climatic conditions such as drought or wetness?

The first part of this analysis dealt with the effect of topography on BAI over an extended period of climate history. This part of my analysis deals specifically with how mean BAI and CV BAI were affected by topographic differences in moisture availability during specific climate events such as periods of drought or excessive precipitation.

Using the BAI time series in Figures 5 and 6 in conjunction with the PDSI time series in Figure 9, I identified distinct periods of time where BAI appeared to be affected by climatic events. These periods are the 1952-1960 drought, 1961-1970 period of normal climate, 1971-1975 period of wetness, 1976-1985 period of normal climate, 1986-1988 drought years, 1989-1997 period of wetness, 1928-1960 previous to the increase in growth, 1961-1985 bubble in growth, and the 1986-1997 period of decline. The 1961-1985 and 1989-1997 periods were previously identified for the presentation of results for Objective 1. I used mean BAI and CV BAI for each of the periods as a dependent variable in multiple linear regression analysis. The specific results of the backward-stepwise selection regression analysis for the WBW Overall population are presented in Tables 1 and 2. The results for the WBW Old and WBW Young subpopulations are presented in Tables 3 and 4, and Tables 4 and 5, respectively.

For the WBW Overall population topographic index was associated with increased growth prior to 1960, but thereafter high topographic index was associated with low growth. High topographic index reduced CV for every time period it was found to be significant. Healthy crown vigor was always associated with increased mean BAI and reduced CV BAI.

For the WBW Old subpopulation, topographic index was rarely found significant as a predictor of mean BAI for the analysis. Topographic index positively influenced mean BAI prior to 1960 but showed no other significance thereafter. Where topographic index was not a significant variable it should be noted that the percent of the basal area that is yellow-poplar basal area was often a significant variable. Topographic index did not have much influence on CV BAI for the analysis. It was also apparent that crown vigor did not play as significant a role as it did for the WBW Overall population. The model R^2 values for the WBW Old regression models were less than the model R^2 values for either the WBW Overall or the WBW Young models.

For the WBW Young subpopulation, topographic index was significant as a predictor of mean BAI for the analysis. Topographic index had no significant influence over mean BAI prior to 1960, but was significant for the other time periods. Increasing topographic index reduced CV BAI prior to 1960, had no significant effect between 1961 and 1985, and increased CV BAI after 1986.

Crown vigor played a very important factor in increasing mean BAI during the 1986-1997 decline. Crown vigor also played a very important role in reducing CV BAI during the decline period.

The final results I present are those obtained from response function analyses that were performed to measure the degree of climate association with BAI. I used Mesic, Intermediate, and Xeric mean BAI time series for the WBW Overall population, the WBW Old subpopulation, and the WBW Young subpopulation as dependent variables and monthly climate data as predictor variables.

According to principles of limiting factors and site sensitivity described by Fritts (1976), climate should explain a greater percentage of variance in BAI of trees growing in xeric locations than for trees growing in mesic locations. I performed response function analyses (Tables A-2, A-3, A-4) and used the model R^2 results as an indicator of sensitivity to climate. Higher model R^2 results are associated with higher levels of climatic sensitivity due to topographic influences on potential moisture availability. The WBW Overall/Mesic regression model has a model R^2 of 0.4822. The WBW Overall/Xeric regression model has a model R^2 of 0.6185 and the WBW Overall/Intermediate model having and R^2 of 0.5000. These results indicate that there was a difference in the climatic influence on BAI between mesic and xeric locations.

The WBW Old/Mesic, WBW Old/Xeric, and WBW Old/Intermediate models have R^2 values of 0.4149, 0.4971, and 0.3811, respectively. The range in R^2 between Mesic and Xeric was not as wide as the WBW Overall models, but there was still a difference in R^2, with the highest value for the Xeric sites, as expected.

The WBW Young/Mesic, WBW Young/Xeric, and WBW Young/Intermediate models had R^2 values of 0.4893, 0.5696, and 0.4795 respectively. Again, the Xeric group had the highest R^2 value.

I was able to reproduce similar model R^2 results using the overall WBW population and subdivisions of the overall population. In all cases, climate explained more variance in the Xeric groups. The Intermediate groups were very similar to the Mesic groups. The model R^2 results were also consistent with the ANOVA results for differences in CV BAI group means; CV BAI was always higher for the Xeric groups.

CHAPTER V

DISCUSSION

This study found significant relationships between variation in BAI and changing temporal and spatial levels of moisture availability. The discussion of these relationships is presented in accordance with the objectives to which they pertain.

Growth Trends

The first objective was to determine the occurrence and probable causal factors of any long-term changes in yellow-poplar BAI. Two distinct trends in growth have occurred since 1928. The first trend was abnormally high growth that occurred between 1961 and 1985. The second trend, which was hypothesized for Objective 1, was the very significant decline in growth that occurred in 1986 and lasted through the end of the study period (1997).

Using regression analysis to develop response functions, both variance associated with growth trend linked to serial correlation and variance associated with growth trend linked to climate were removed from the mean BAI time series. The serial correlation, or autoregression, was discovered during the development of the response functions, which tested the association between climate variables and annual BAI. It was determined that the autoregression should be removed if the response function analyses were to be

accepted as valid. The residual BAI time series were examined after the variance associated with autoregression was removed, and a noticeable reduction in both of the major growth trends was apparent. The BAI time series with variance associated with autoregression removed, or "whitened" BAI time series, were then regressed against monthly climate data. The residuals from these regressions were examined and the two major growth trends were again further reduced. An examination of the final set of BAI residuals with climate and autoregressive associations reduced, showed that the trends in mean BAI were mostly removed.

There was some interest that these trends could be indicative of changing stand or site characteristics, such as the succession of forest stands, changes in soil nutrient levels, or even anthroprogenic pollution disturbances. This analysis has shown that changing stand characteristics and site characteristics can be ruled out as the principal causes of the growth trends. The autoregressive properties of annual wood production in association with climatic influences were the probable causative factors of the two major growth trends.

Starting around 1961 the climate began to be more moist and the trees on WBW responded with increasing BAI. Autoregression became a factor in the increase in BAI at this time because energy stored during one growing season has a very significant effect on growth the following growing season (Fritts 1976). With many subsequent wet growing seasons in association with stored energy reserves, BAI "snowballed" and growth continued to increase through 1973. In 1974, BAI moderated and began to level off. Growth remained fairly constant for the next decade until 1985 when another significant climatic event occurred.

In 1985, a major drought began of a length and severity unparalleled in the previous one hundred years of climate history, according to NCDC climate records (1999). In 1986, growth showed a very sharp decline and remained very low during and long after the end of the drought in 1989.

After the 1980's drought, climate changed again and the growing seasons became wet which should have been beneficial for BAI. However, growth rates of the trees did not respond significantly to the increases in moisture. It is not known why the trees had not recovered by the time this study began in 1998. It is likely that the 1980's drought was of such severe intensity and length that it may have impacted the ability of the yellow-poplars to recover and show any significant positive response to the increases in moisture that occurred in the 1990's.

Tables 1 through 6 show that crown vigor played a significant role in mean BAI during the 1986 to 1997 decline. This indicates that trees that either had healthy crowns at the start of the drought or had little loss of live crown during the drought maintained greater levels of growth during the decline than trees with poor crowns. The crowns and/or root systems of the trees probably suffered from die-back. This die-back could have been intensified because the trees were not physiologically adapted to drought stress since the climate had been moist to very moist for the 25 years previous to the onset of the 1980's drought. No studies have been performed to determine if the yellow-poplars on WBW have shown any signs of recovery since 1997.

It is interesting to note that long-term BAI response to the 1950's drought, which also lasted for several subsequent years, is different from the long-term BAI response to

the 1980's drought. The 1950's drought was not nearly as severe in intensity as the 1980's drought. The 1950's drought is classified as moderate in intensity, while the 1980's drought is classified as severe to extreme in intensity. This may account for the ability of the trees to recover following the 1950's drought. Also, the decades previous to the 1950's drought were characterized with alternating drought and normal climatic conditions. The trees may have been more physiologically adapted to drought stress in the 1950's than they were in the 1980's.

It is also possible that the 1986 to 1988 drought was only the initiator of the decline. Perhaps some other factor such as a reduction in vigor due to an insect pest or pathogen reduced the trees ability to recover from such a severe period of drought stress. For example, stress associated with bud and foliage damage from repeated outbreaks of the yellow-poplar weevil (*Odontopus calceatus*) may have prevented the trees from recovering from the drought initiated decline.

It is encouraging that the yellow-poplars in this study occupied the dominant and co-dominant crown positions. If the trees are going to recover from the decline that resulted from the 1980's drought, then their dominance in the forest should assist. However, there are serious implications for the future of yellow-poplar as a dominant forest species on WBW. If there is no significant recovery from decline, the processes of forest succession may lead to an early exclusion of yellow-poplar from the role as a dominant presence in the forest stands of WBW. Unless major disturbances of the forest occur to create new areas for yellow-poplar colonization, yellow-poplar may have a limited future at WBW.

Role of Topography

The second objective was to determine the role of topographic position on temporal and spatial variation in BAI. Climate is the principal limiting factor that influences temporal variation in growth. With changes in climate there are related changes in annual BAI. The influence of topography on yellow-poplar's BAI response to temporal changes in climate was determined.

Topography creates a fine-scale moisture gradient and trees at different locations along that gradient experience different levels of soil moisture; therefore, variation in growth changes along the moisture gradient. Topographic index was used to measure the location of each tree along the moisture gradient.

Temporal change in growth was measured by determining mean BAI and coefficient of variation (CV) of BAI during climatic periods. These periods range from sixty years of general climatic history to specific climatic events such as drought or wetness.

During specific climatic events such as drought, normal, and wet periods topographic index showed small but significant measurable effects. For the period of relatively normal moisture levels from 1928 to 1952 topographic index had a positive influence on mean BAI production. During the wet period from 1961 to 1985 topographic index had a negative influence on mean BAI production. This was true for the Overall and Old population categories. Topographic index showed no significant influence over the period of time prior to the 1961 to 1985 wet period for the Young

population category and topographic index had a negative influence on mean BAI production during the 1961 to 1985 wet period. Topographic index showed no significant influence on mean BAI production during the 1986 to 1997 decline period. However, CV BAI generally decreased with increasing topographic index regardless of the specific climatic period.

Over the sixty year period of climate history, the results of the ANOVA and multiple linear regressions showed that trees growing at the driest locations had more variability in BAI than trees growing at the wettest locations. This was true for the entire yellow-poplar population and for the Old and Young subpopulations. BAI production became significantly more variable as topographic index decreased.

The results of the response function analysis also indicated that trees growing on xeric locations had a stronger climate signal than trees on mesic locations. This was true for the Overall population, and the Old and Young subpopulations. Trees on sites with low topographic index had increased sensitivity to climatic inputs and therefore increased long-term temporal variation in growth.

However, mean BAI did not appear to be affected by topographic position over a long period of time (1928 – 1997) as did variability of BAI. Between 1928 and 1997 mean BAI did not change as topographic index changed. For example, the WBW Overall/Mesic group had a mean BAI of 24.06 cm^2/year while the WBW Overall/Xeric group had a mean BAI of 24.92 cm^2/year during this time period. The mean BAI between these two topographic categories was not significantly different. Likewise, there was no significant difference when the Intermediate groups were compared with the

Mesic and Xeric groups. The Old and Young subpopulations showed similar results to the Overall population.

Averaged over the years from 1928 to 1997, yellow-poplar at WBW grows at relatively the same rate regardless of topographic index. However, the growth rate, which over time had the same mean regardless of topographic index, did become more variable as topographic index decreased.

It was hypothesized in Objective 2 that trees on mesic sites would have a higher mean BAI, but this was not the case for the trees and the time period in this study. During the 25 year wet period, there was probably enough moisture at all topographic positions to foster strong growth rates. However, during the long period of moisture surplus, trees on xeric locations outgrew the trees on mesic locations.

A major tenet of dendrochronology and ecology, 'The Principle of Limiting Factors', may provide an explanation. During dry periods, trees on mesic locations were nearer the optimum level of soil moisture for yellow-poplar growth than were trees on xeric locations. When climate changed and became wetter, excessive moisture may have become more limiting to growth of trees on mesic locations than to trees on xeric locations. Rainfall was plentiful and the moisture inputs were too great and too frequent for the mesic site soils to drain properly.

Soils on ridgetops did not have much moisture inflow from upslope drainage area and soils on steep slopes drained rapidly. These soils had time to dry between the frequent inputs of rainfall. Therefore, the trees growing on these xeric locations may have been more optimally situated for growth during periods of high moisture than were trees on mesic locations.

Over the balance of many decades and changing climatic conditions, the optimum soil moisture range alternated between mesic and xeric locations. During dry periods trees on mesic sites were more productive and during wet periods trees on xeric sites became more productive. This created a condition where net BAI or mean BAI over many decades was not significantly different among topographic categories.

Topographic index had little influence on mean BAI over time. This does not mean that topographic index had no influence on other aspects of growth response. It was hypothesized in Objective 2 that variation in growth would be influenced by topography with variation being higher on xeric locations. This study has shown that relative variation in BAI production (CV BAI) was significantly affected by topographic index. The use of mean BAI alone would not have indicated significant variation in BAI. However, the inclusion of CV as a measure of variation in BAI revealed that there are significant spatial influences on temporal variation in growth.

It is not well understood how topography affects variation in growth in forests where the regional climate ensures that all topographic locations receive frequent periodic inputs of moisture. This study has shown that fine-scale differences in topography have a measurable affect on variation in BAI of yellow-poplar in a mixed-mesophytic hardwood forest. Yellow-poplar's sensitivity, to temporal variations in moisture, changes as topography influences the potential available moisture of a site.

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APPENDIX

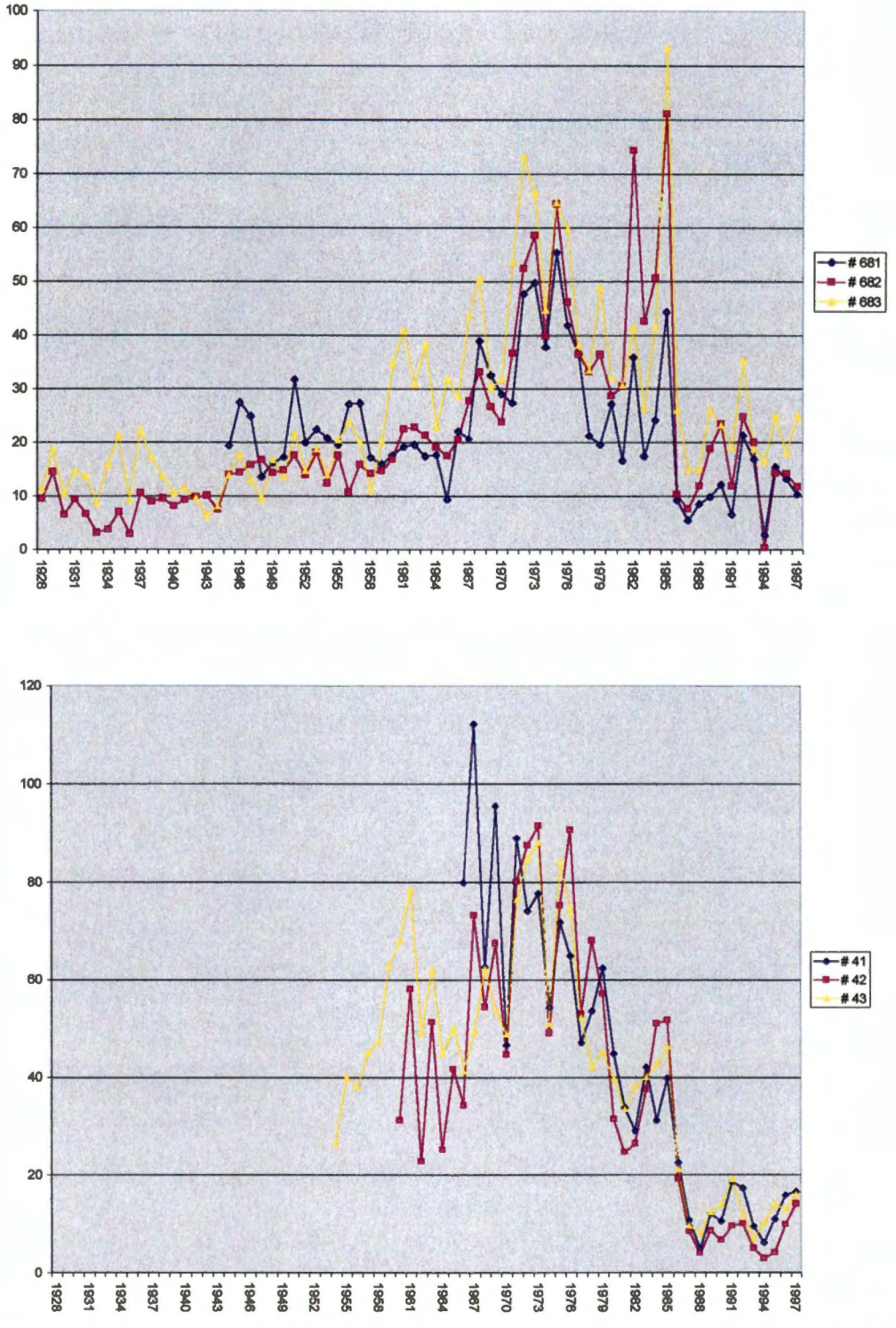


Figure A-1. Individual tree BAI time series plots for Walker Branch Watershed yellow-poplars. Tree plots are organized by the nearest grid station of the coordinate system for Walker Branch Watershed. Grid stations were used as plot centers during sampling. BAI (cm^2) is on the Y-axis and year is on the X-axis.

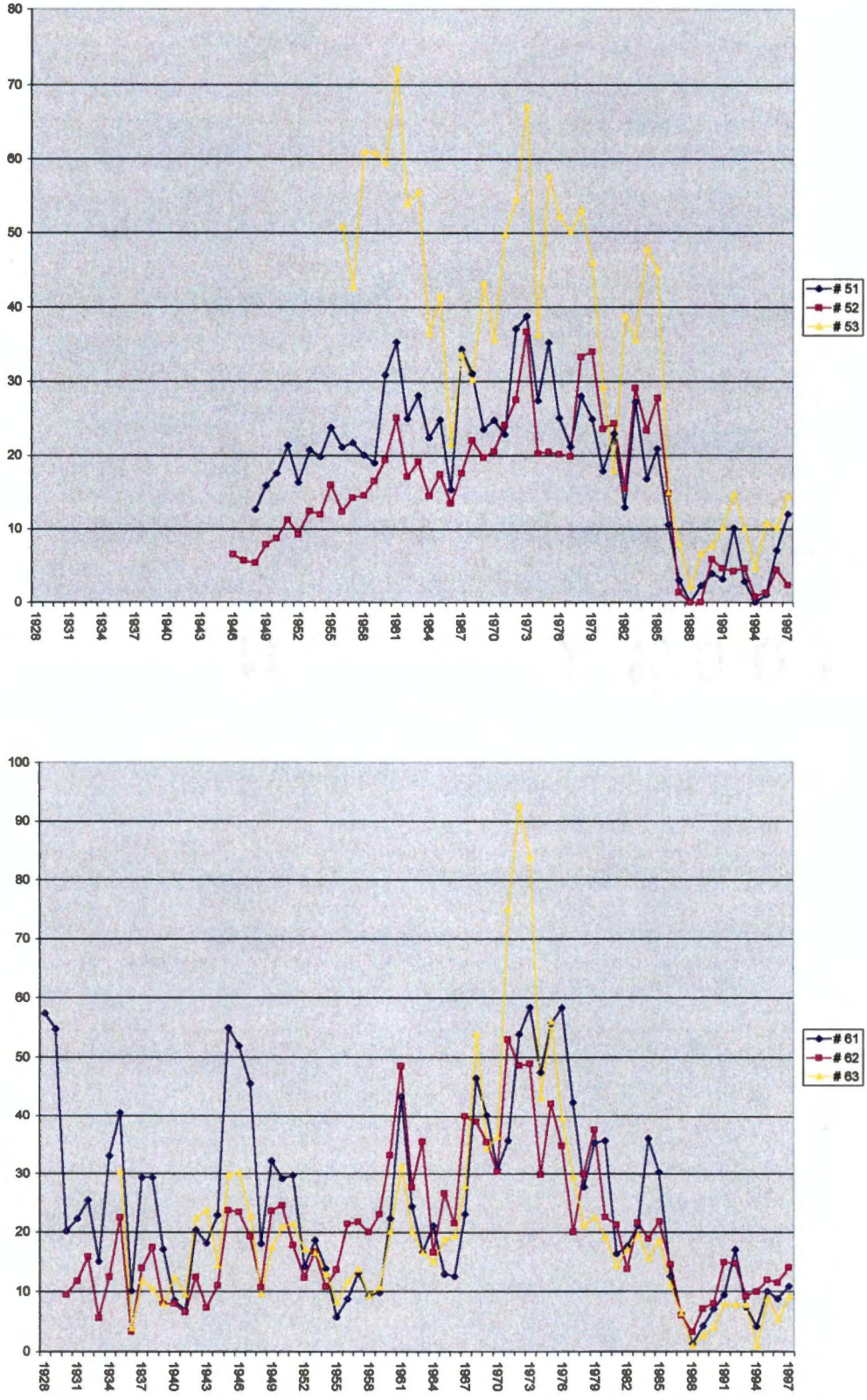
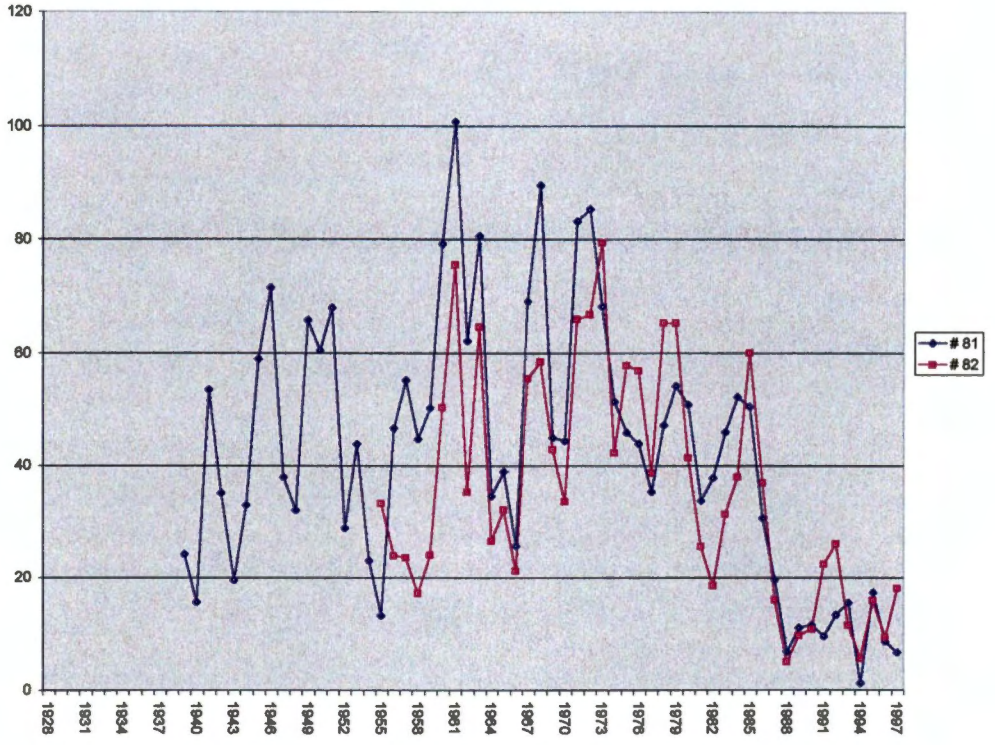


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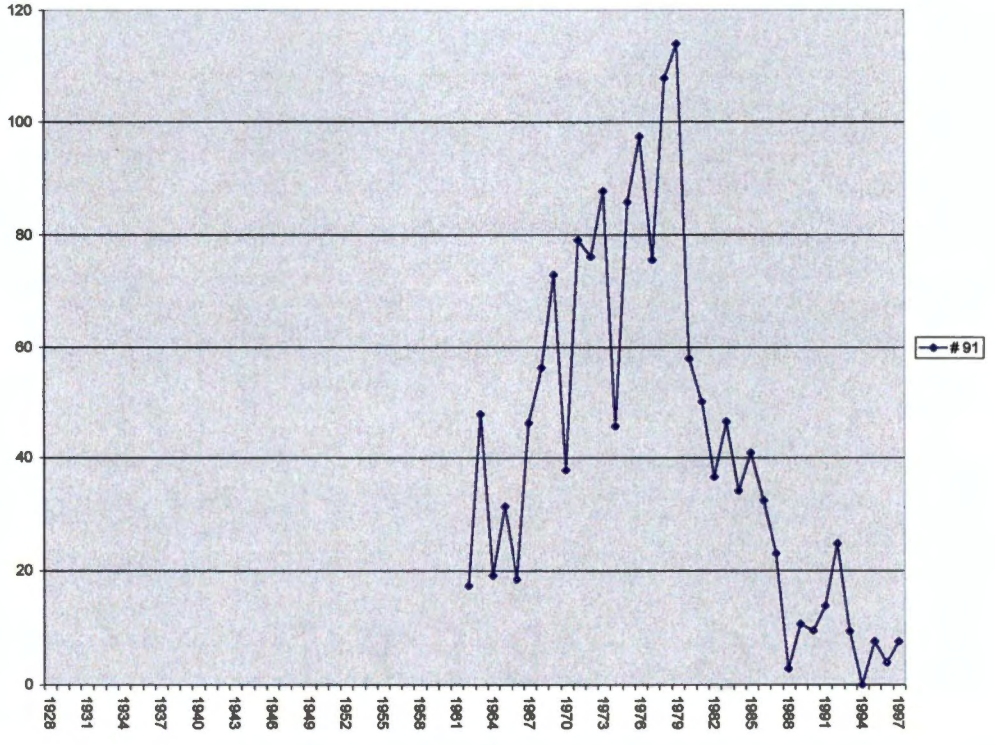


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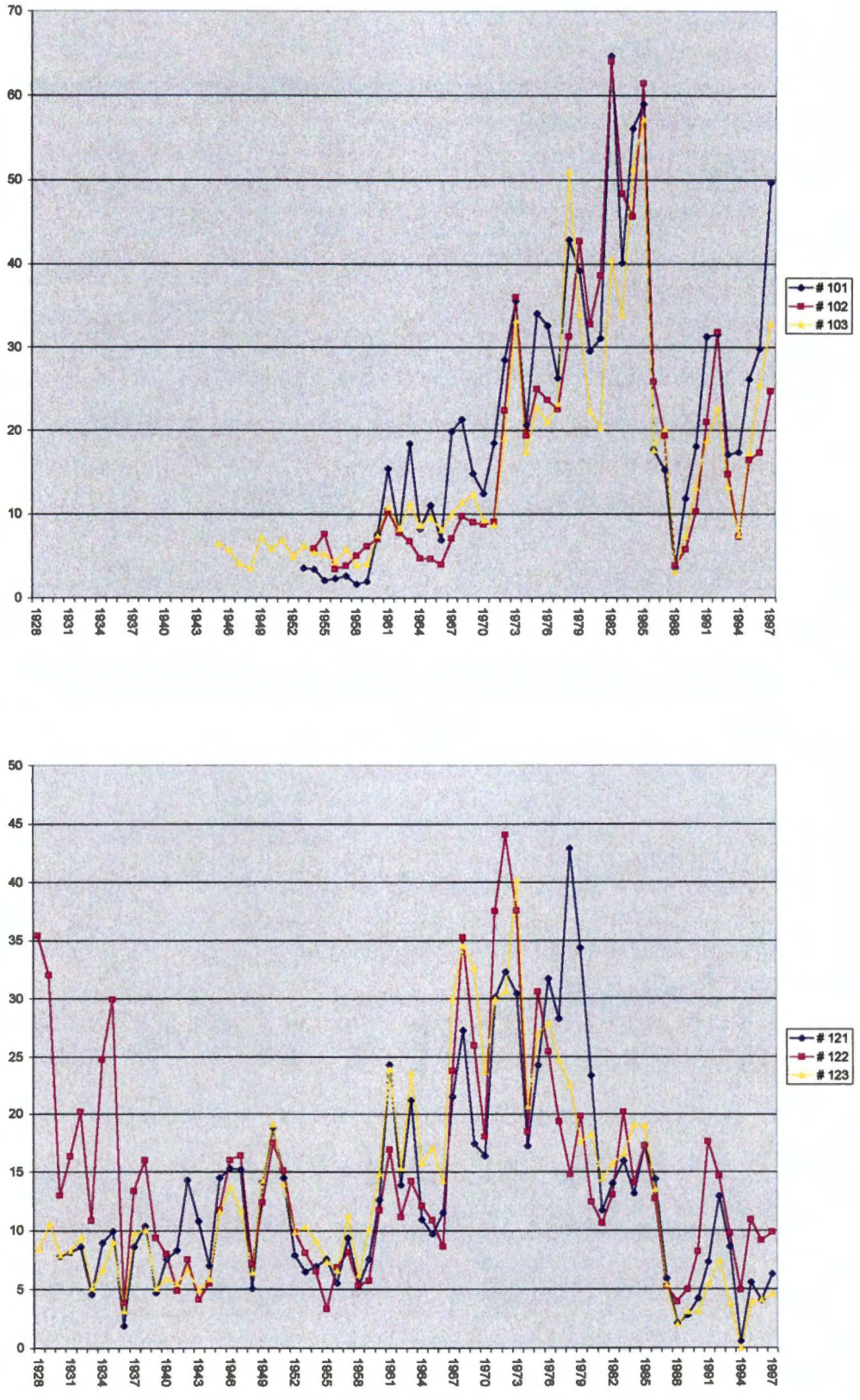


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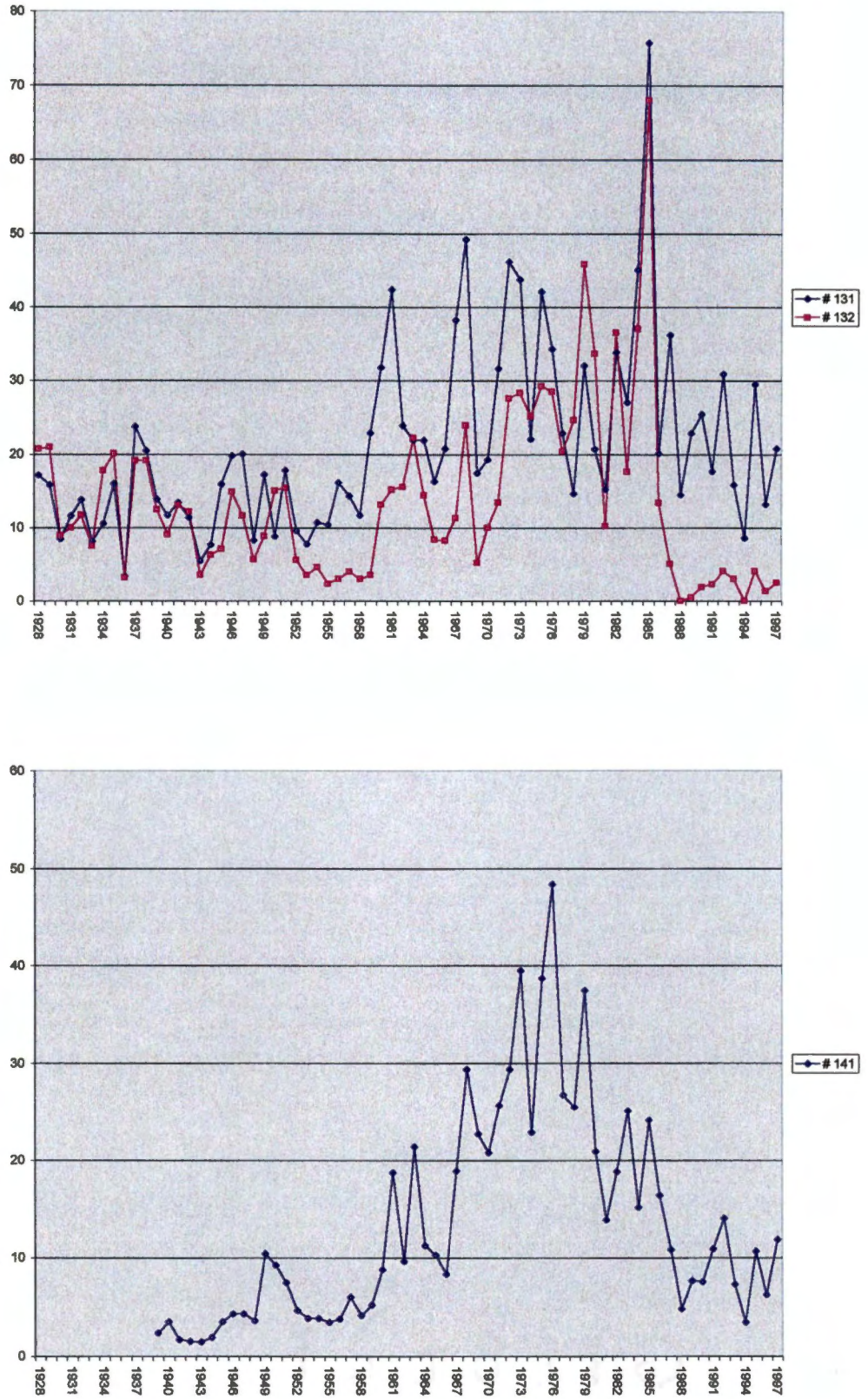


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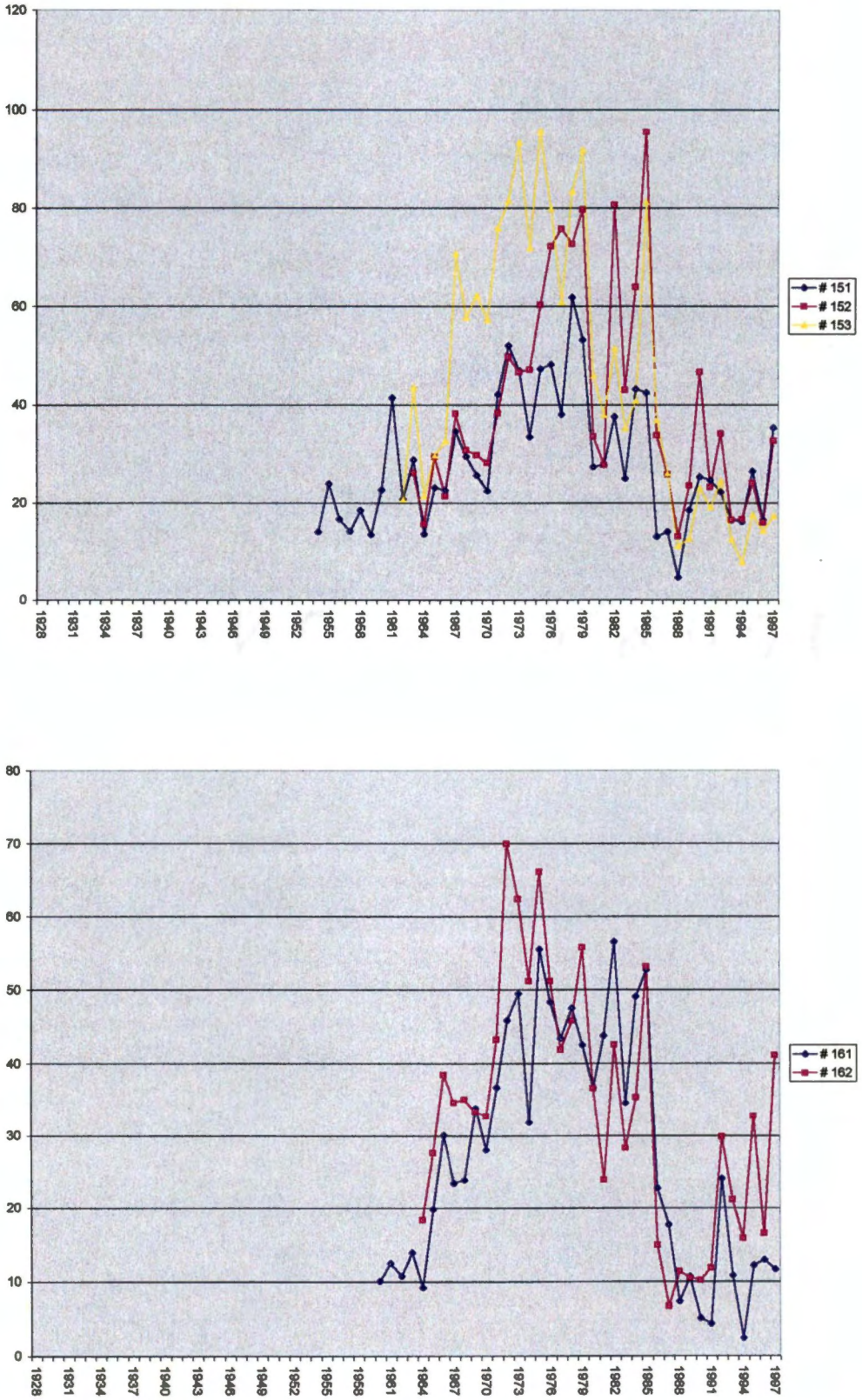
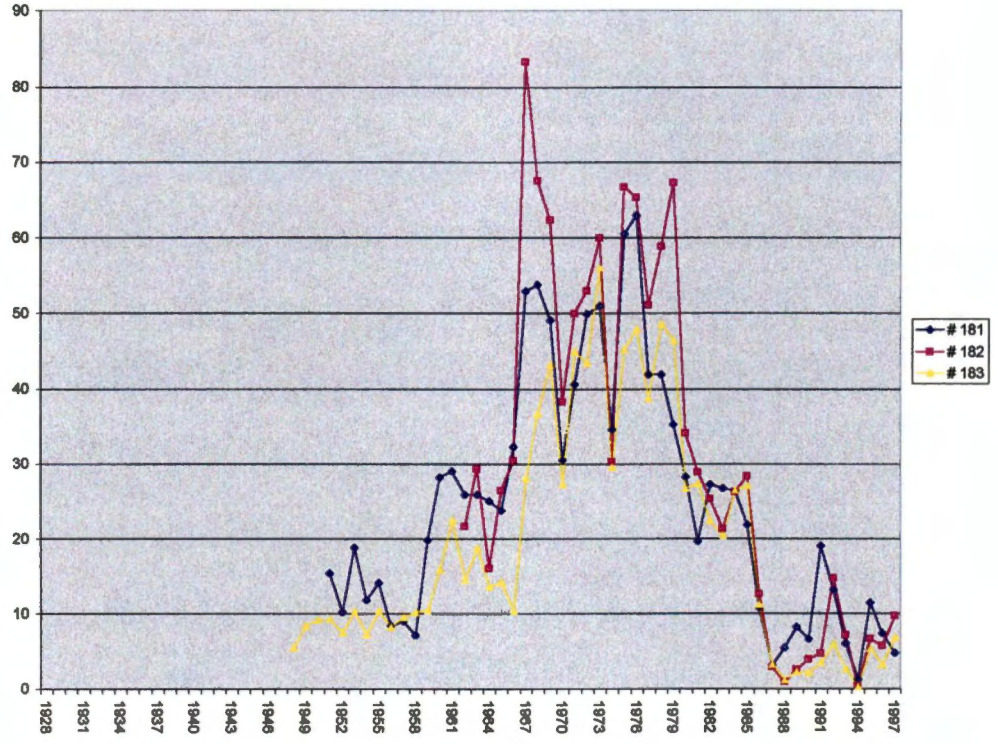


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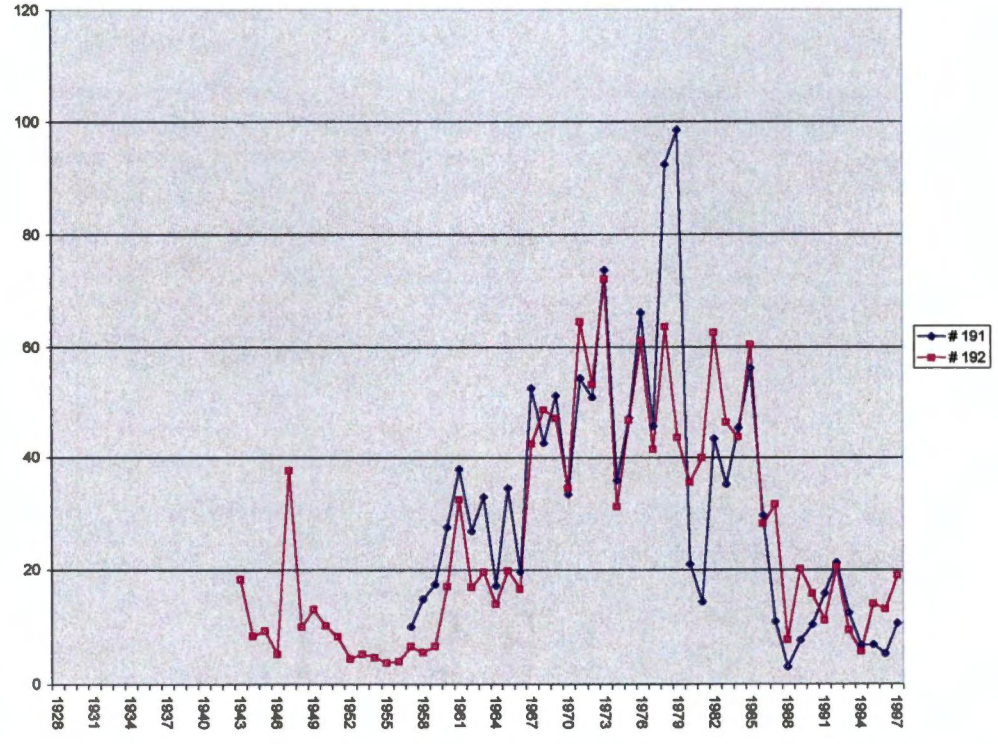


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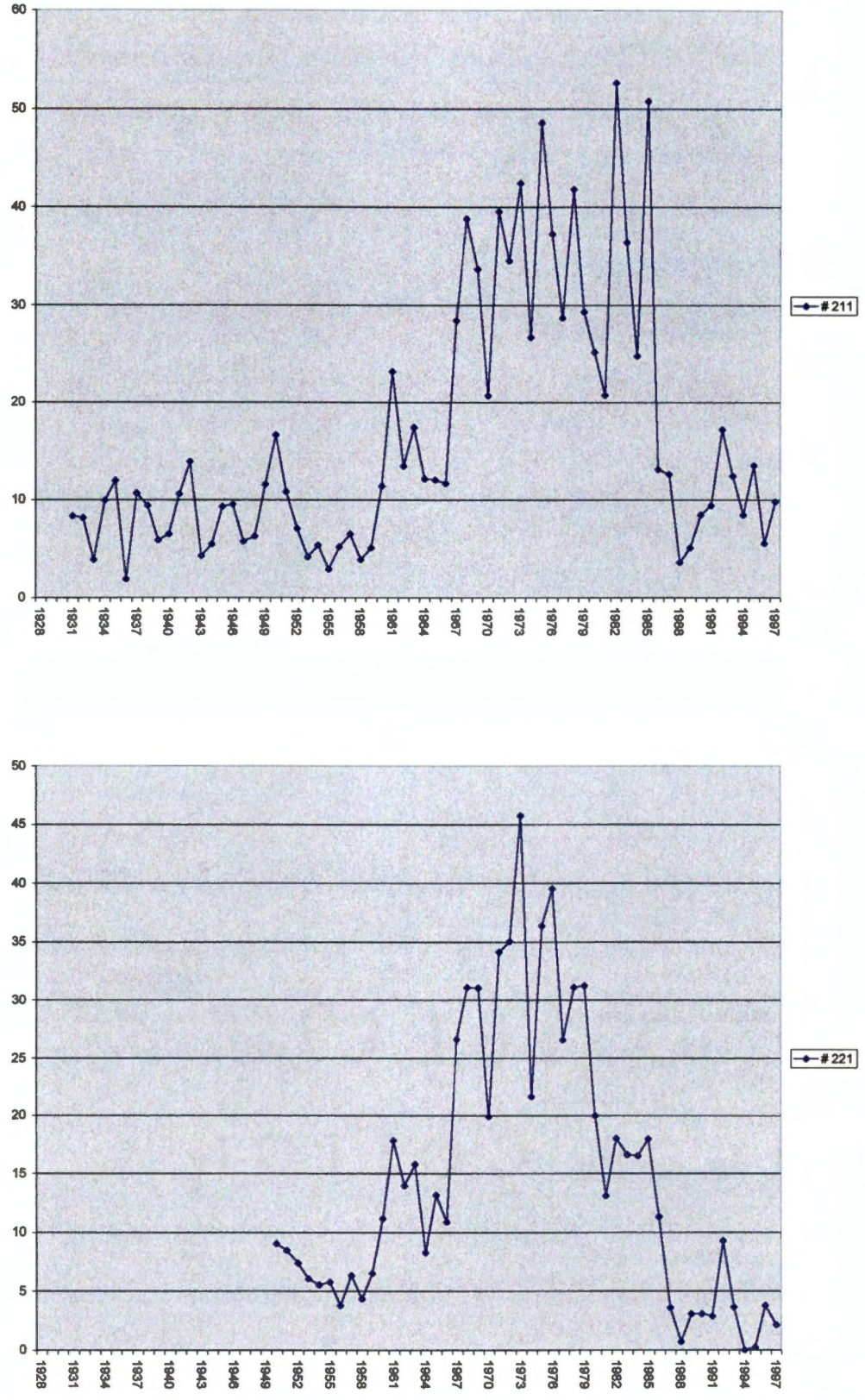
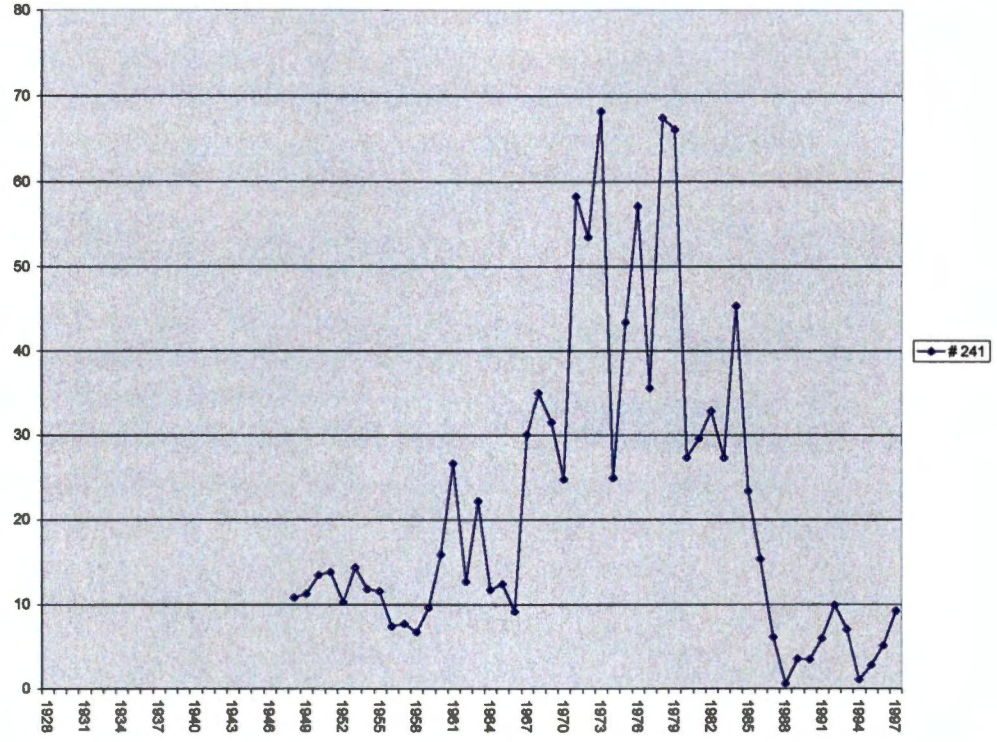


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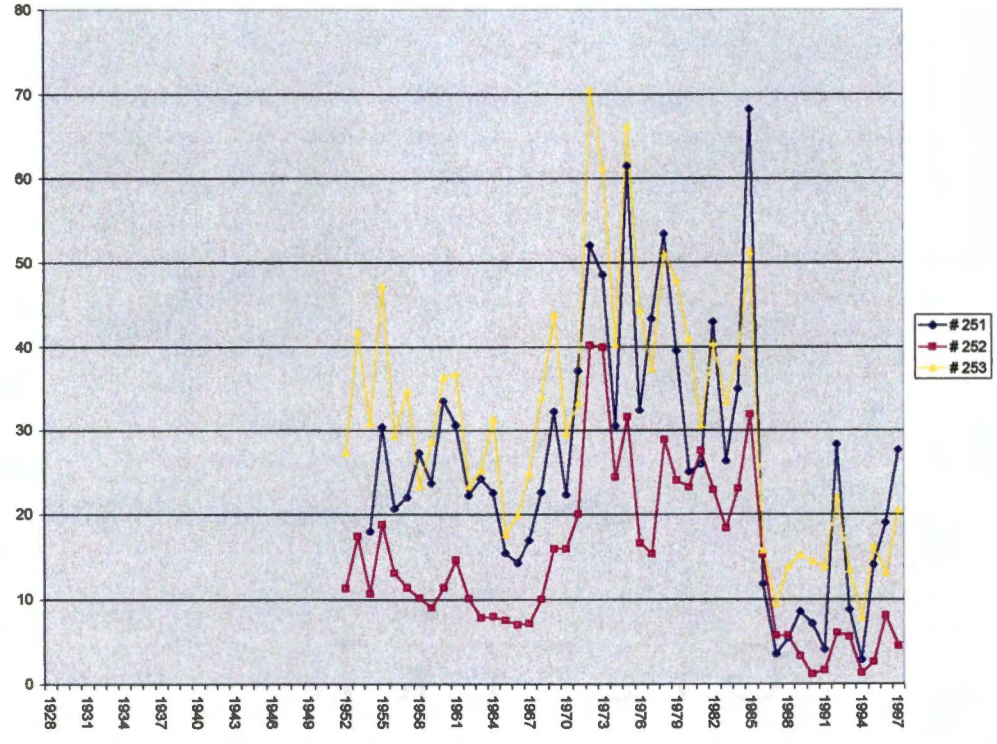


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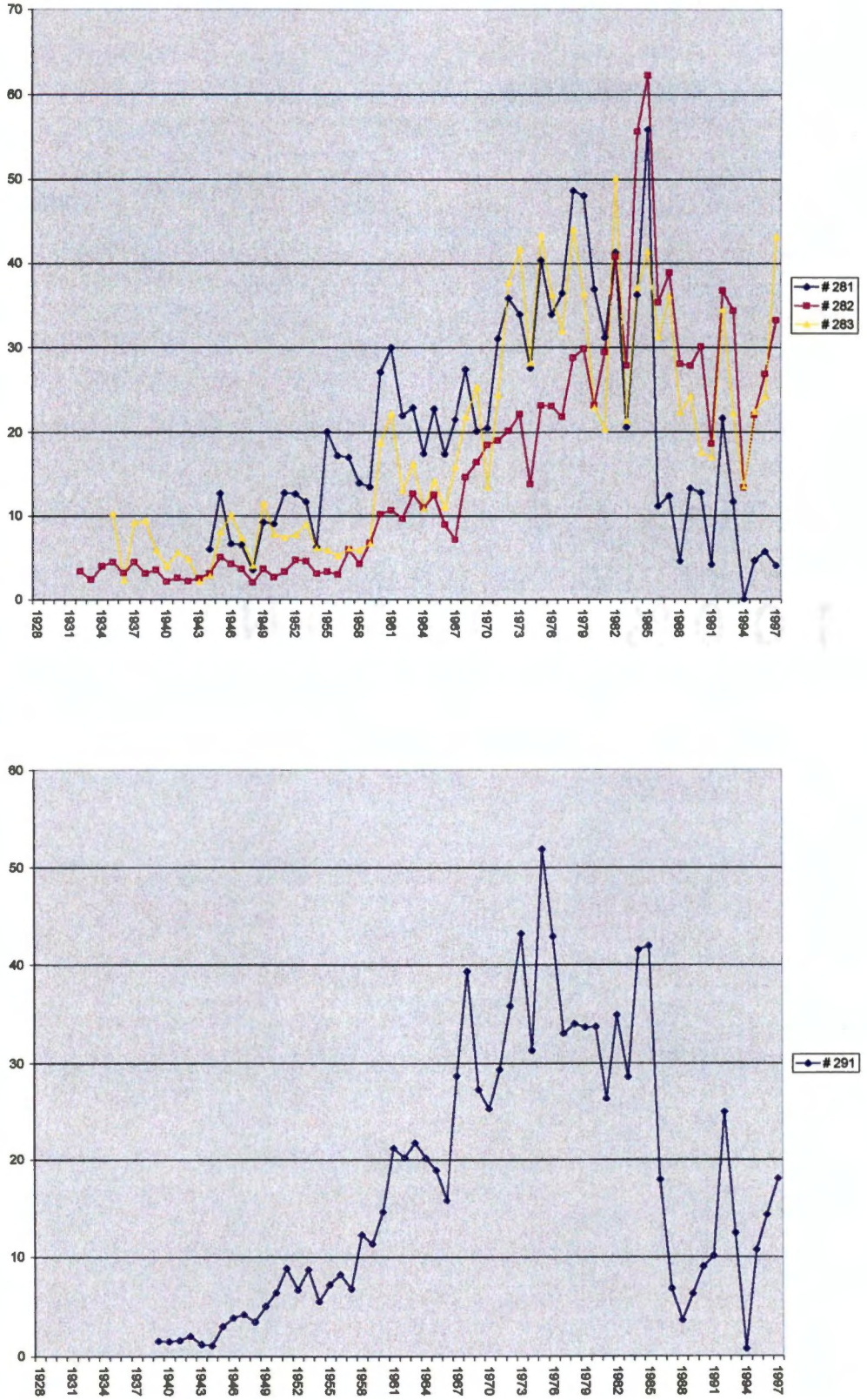
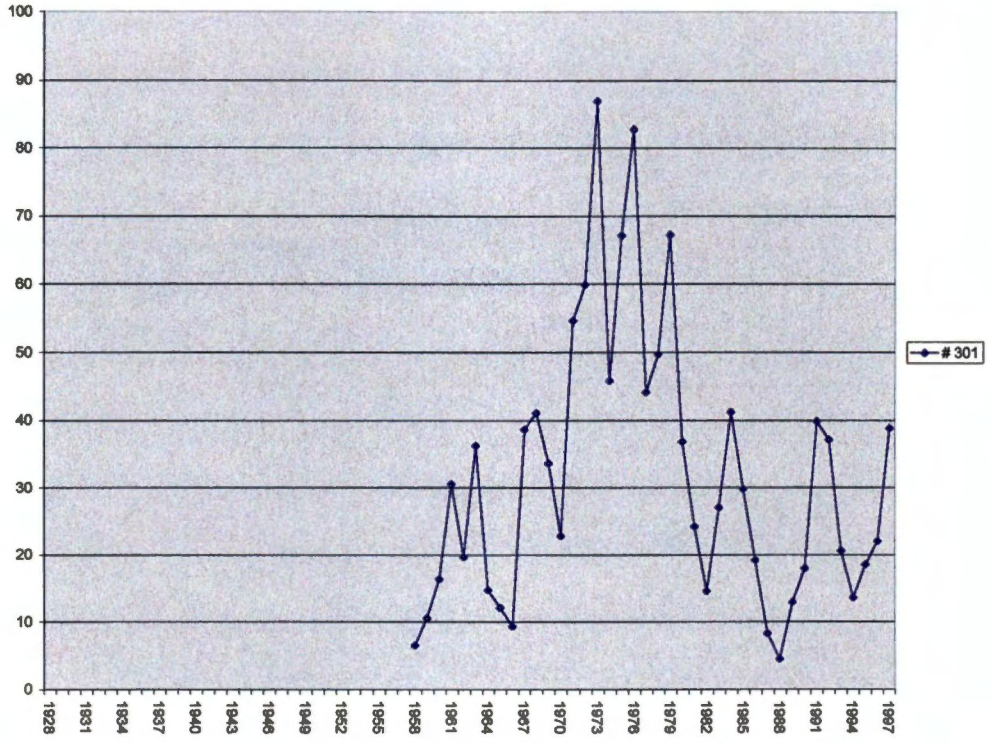


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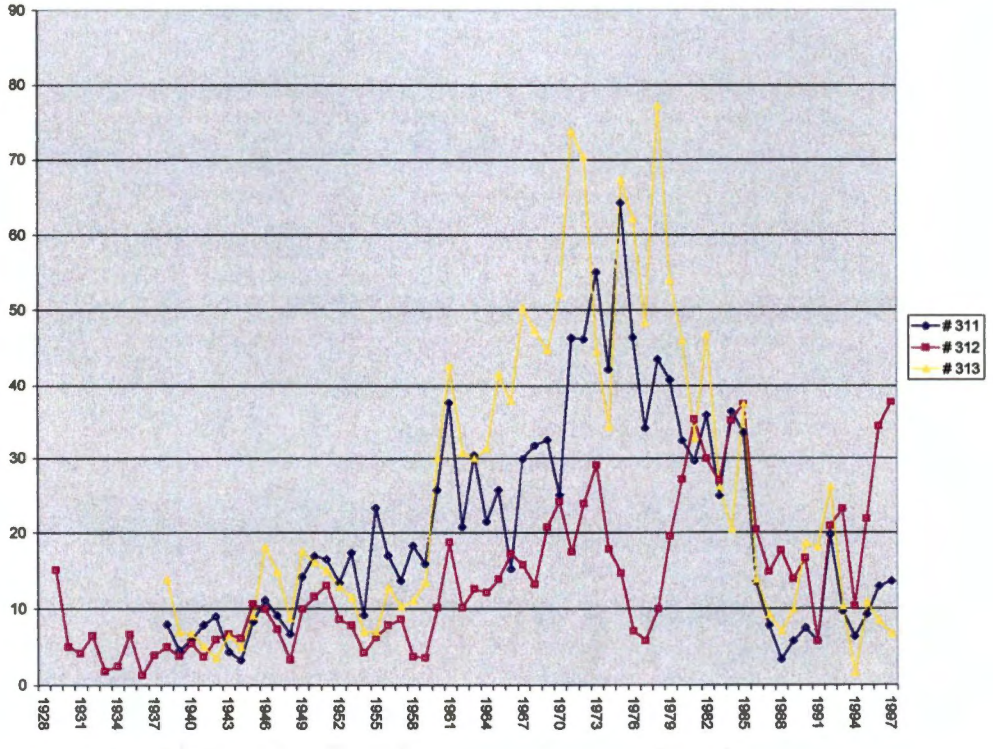


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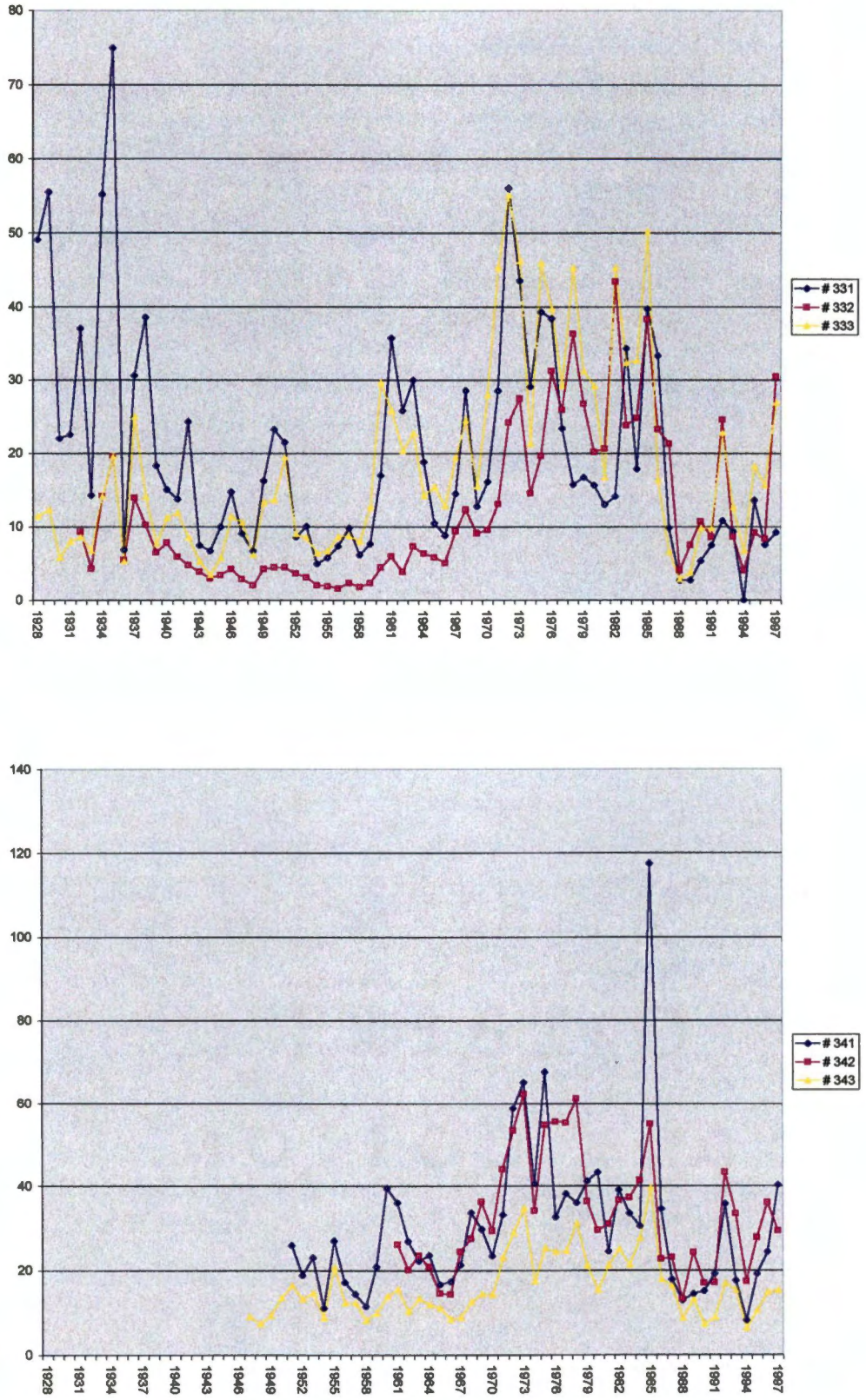


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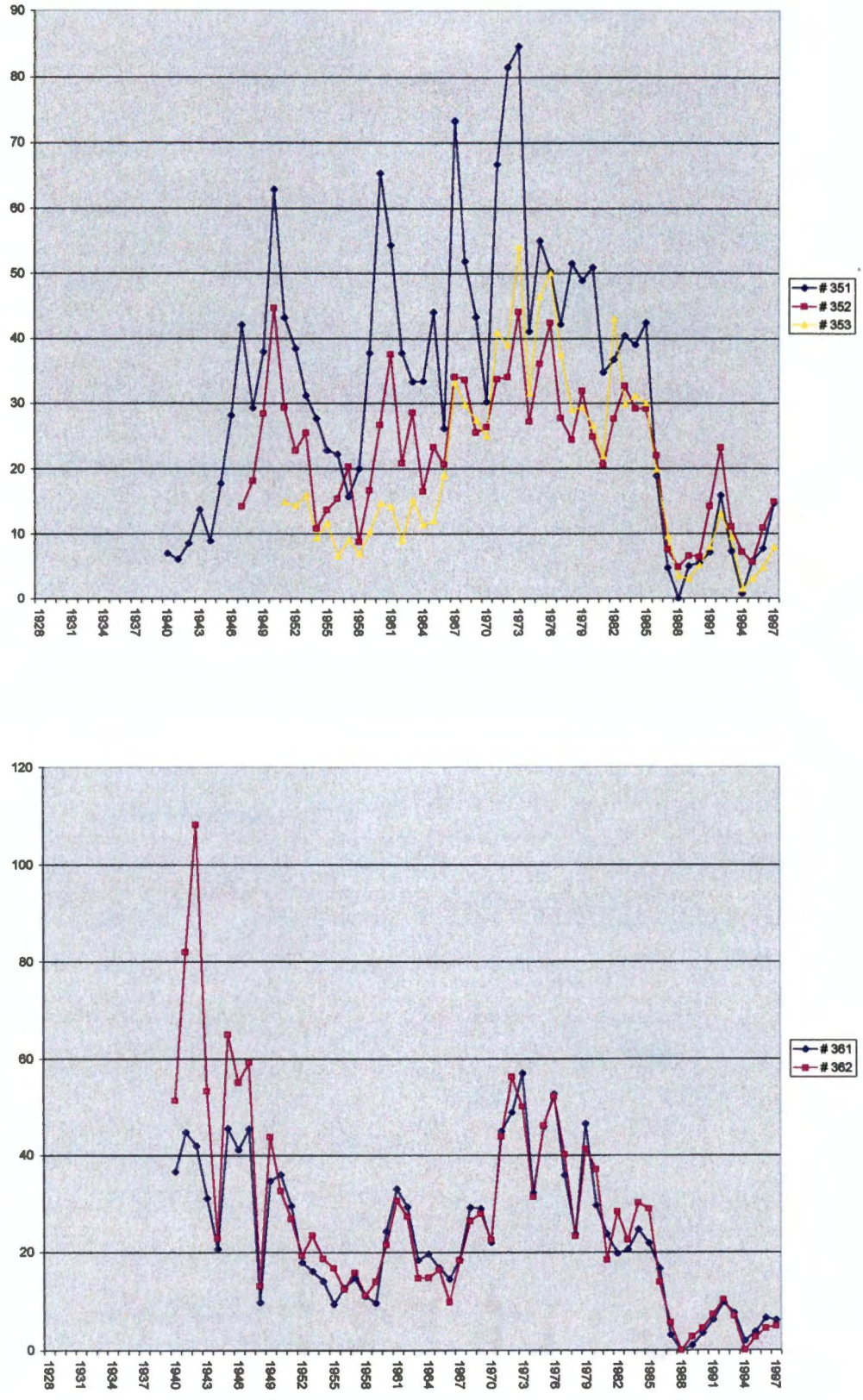
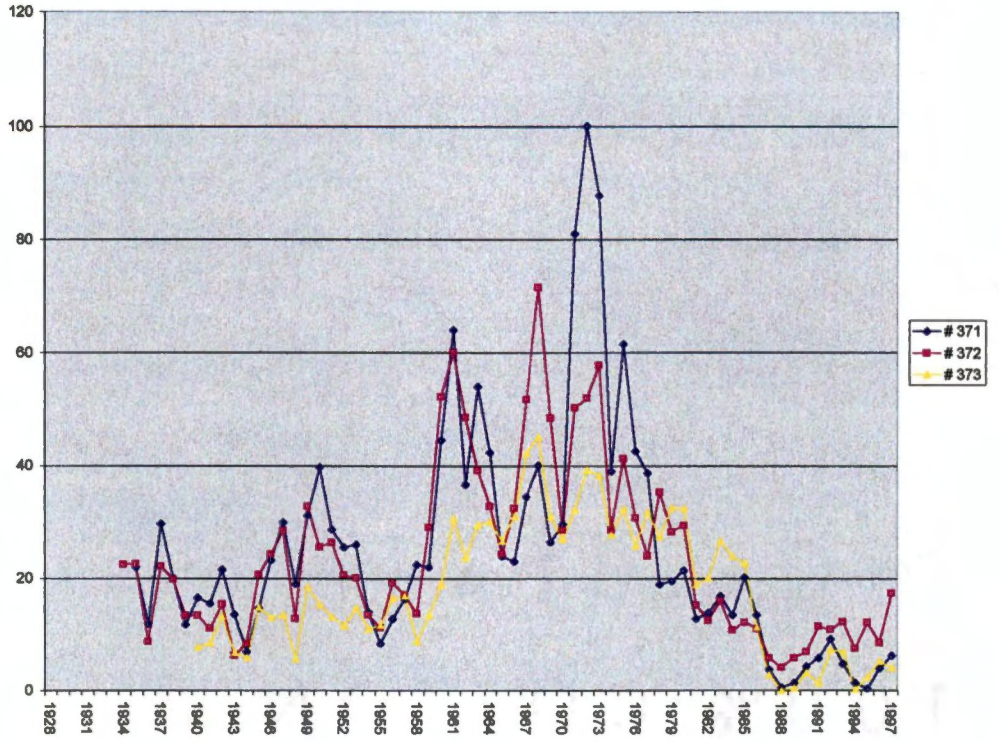


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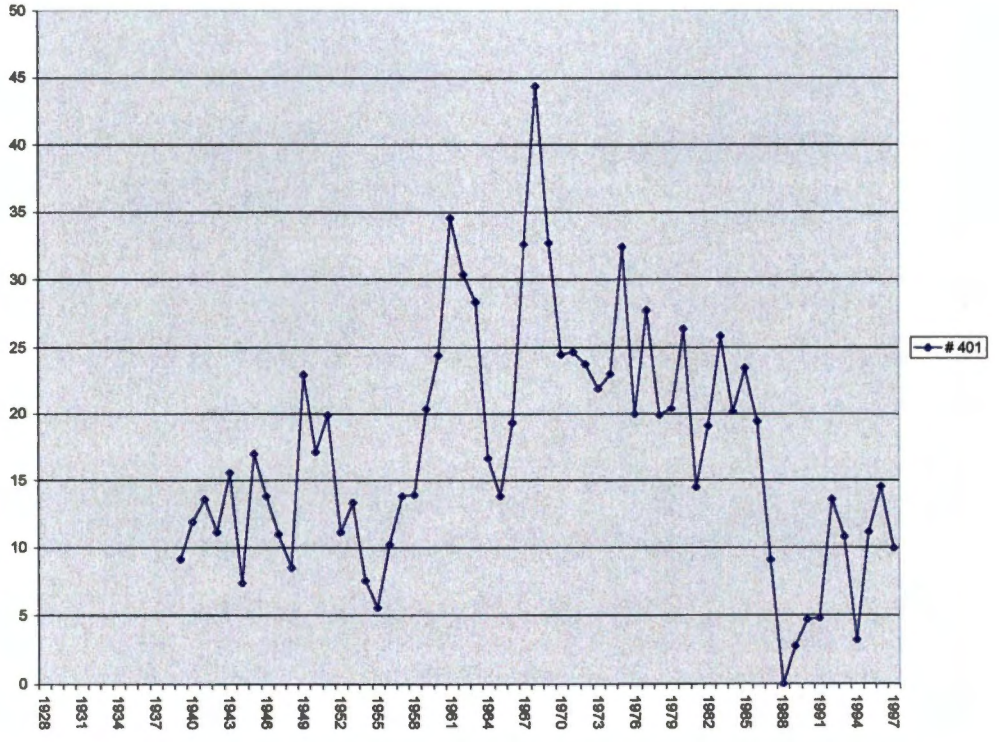


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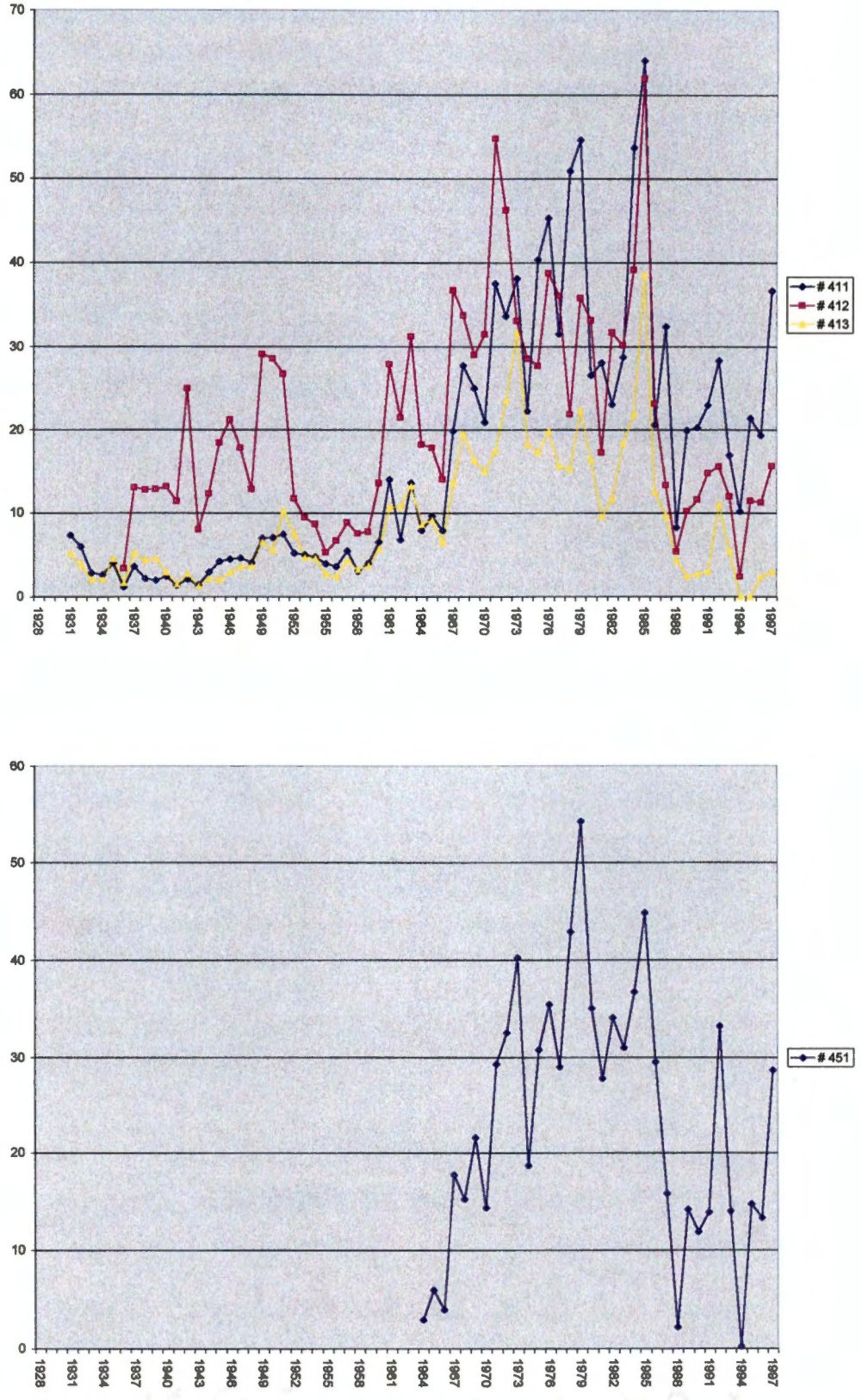


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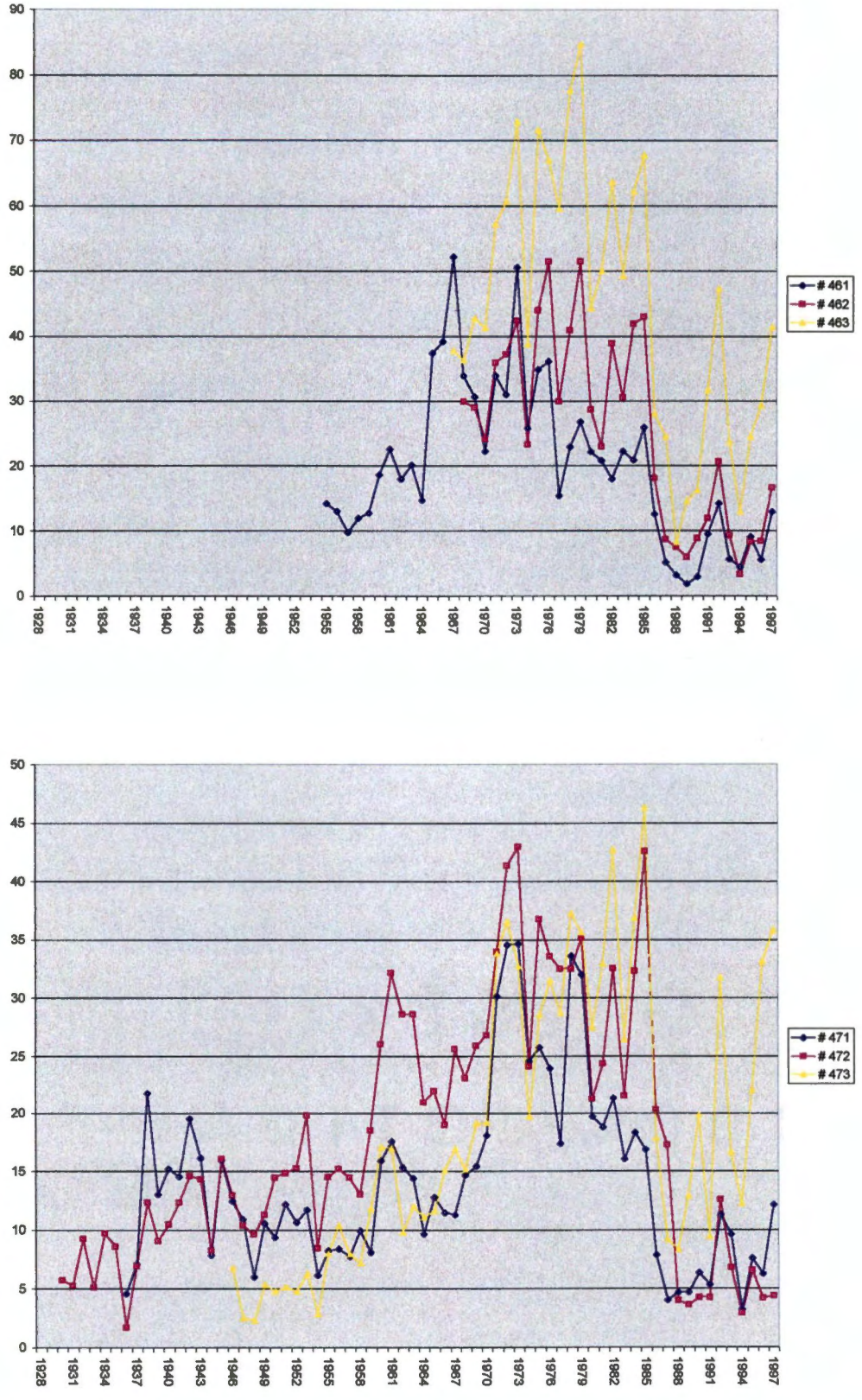
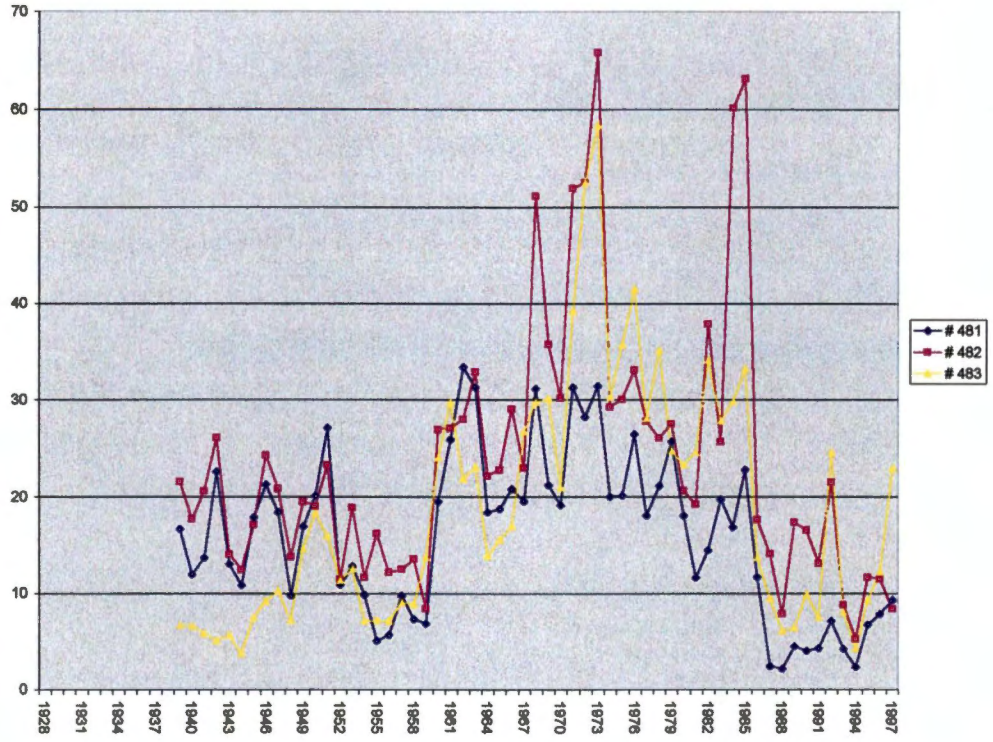


Figure A-1 (continued).



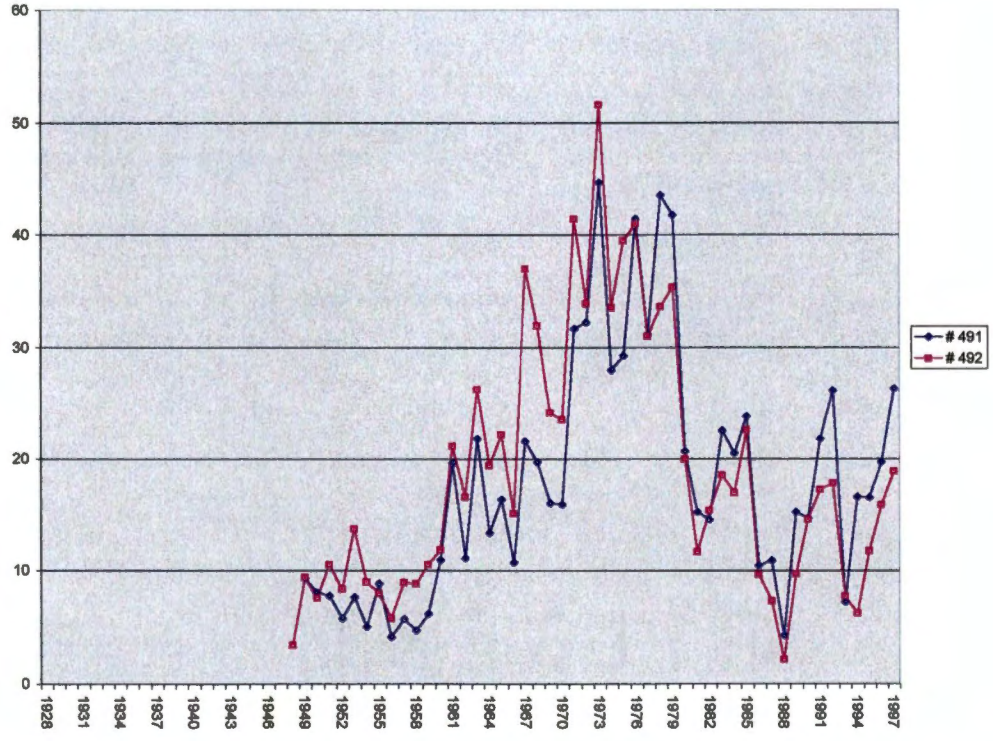
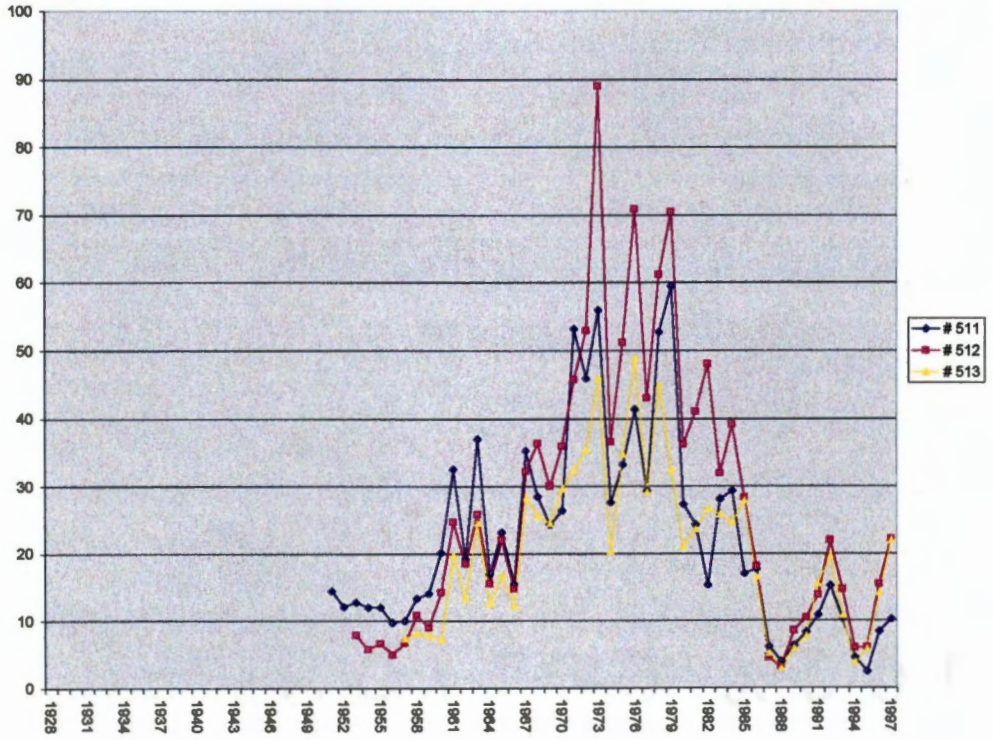


Figure A-1 (continued).



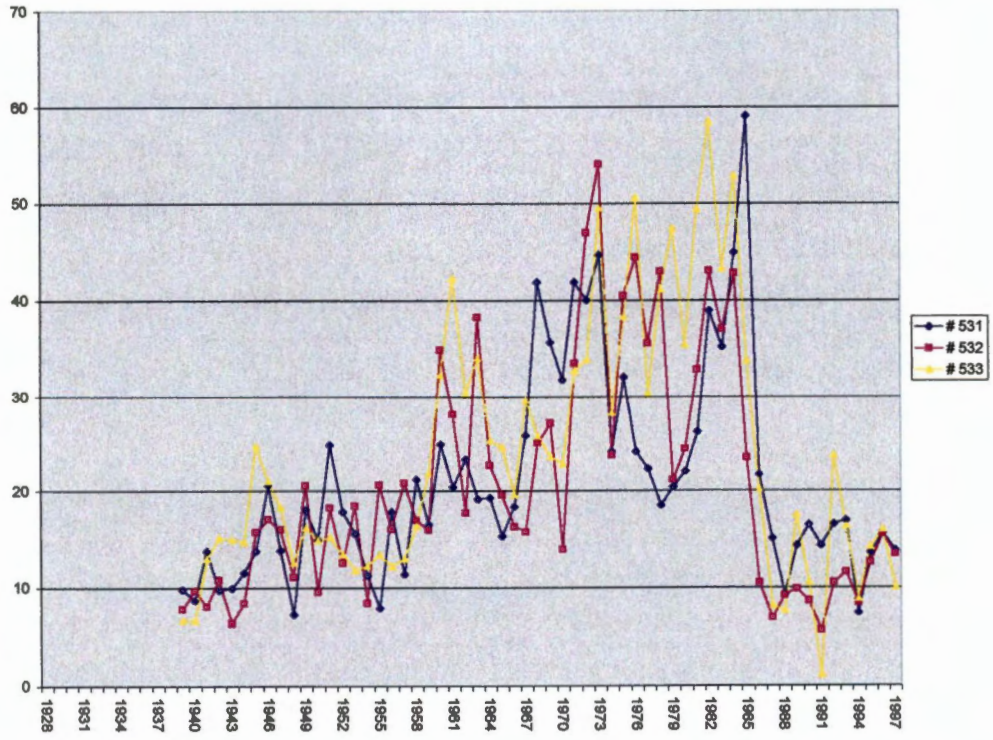
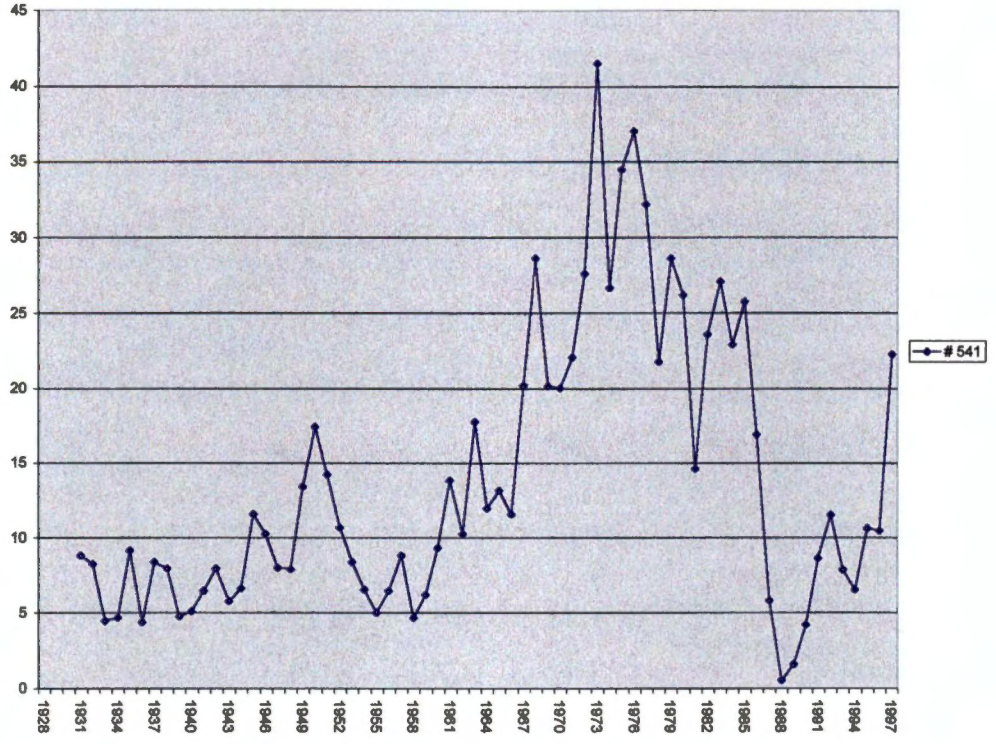


Figure A-1 (continued).



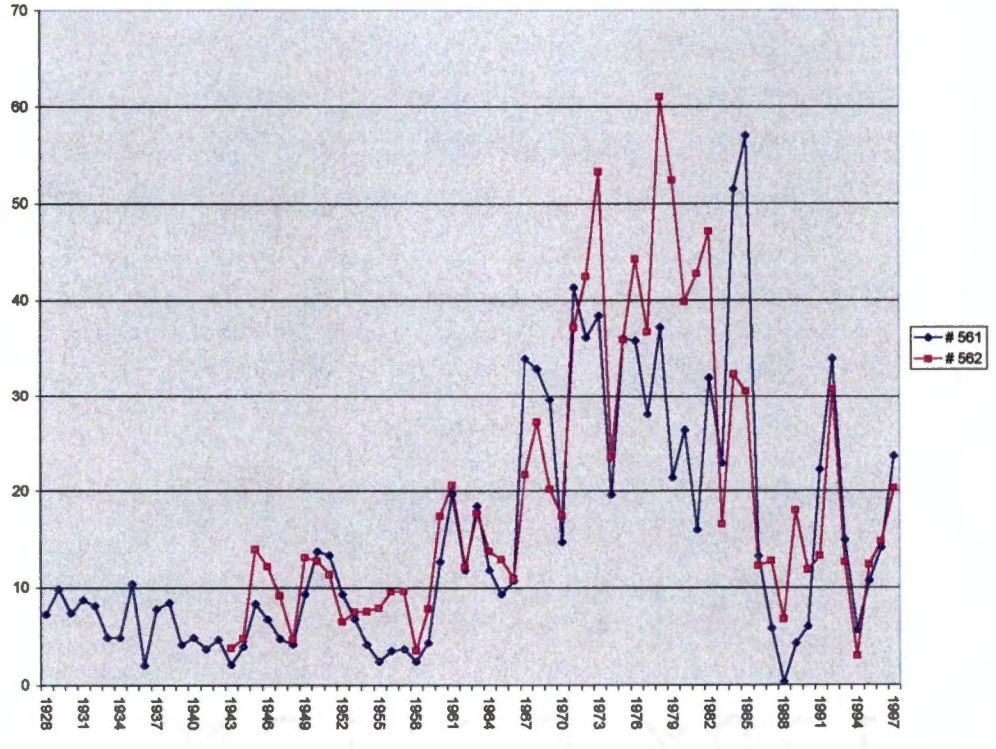
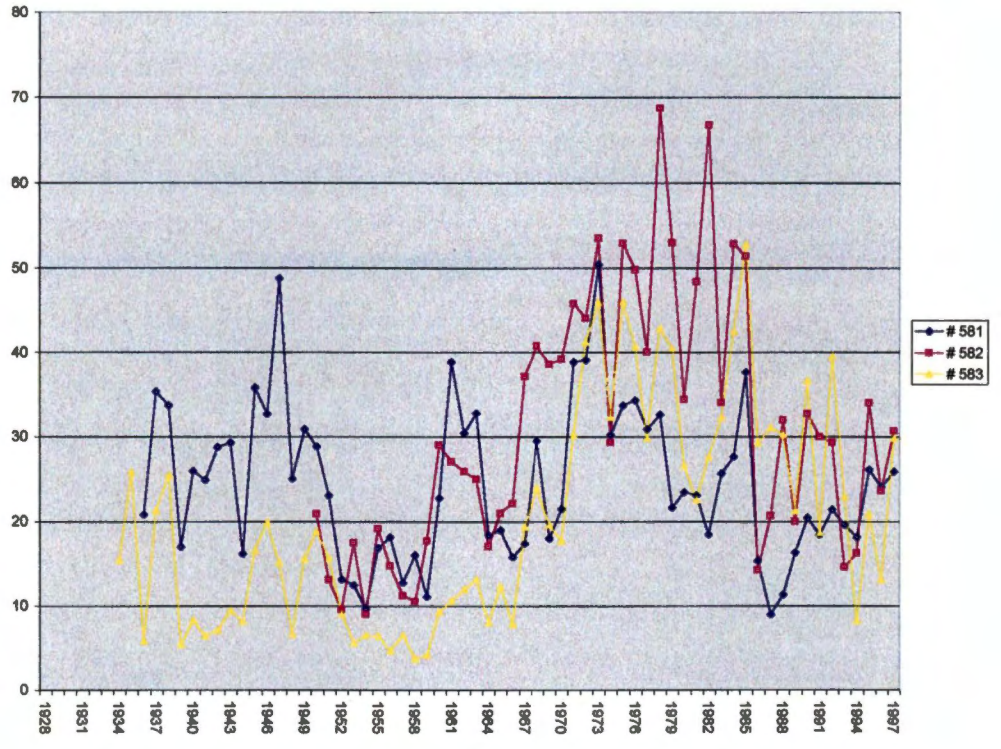


Figure A-1 (continued).



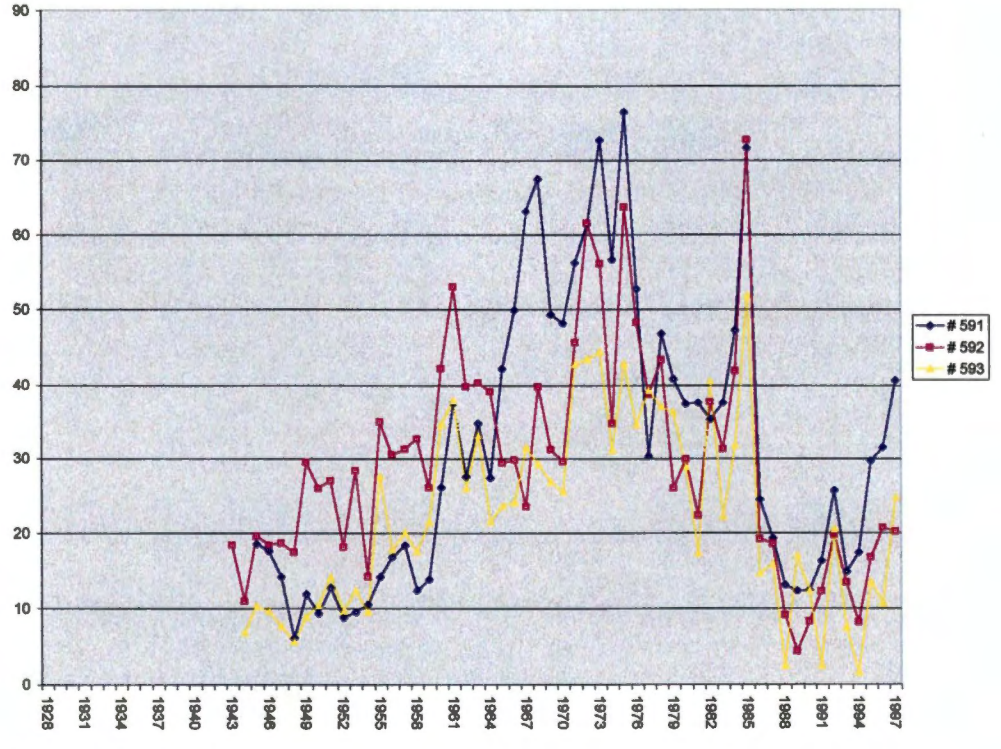
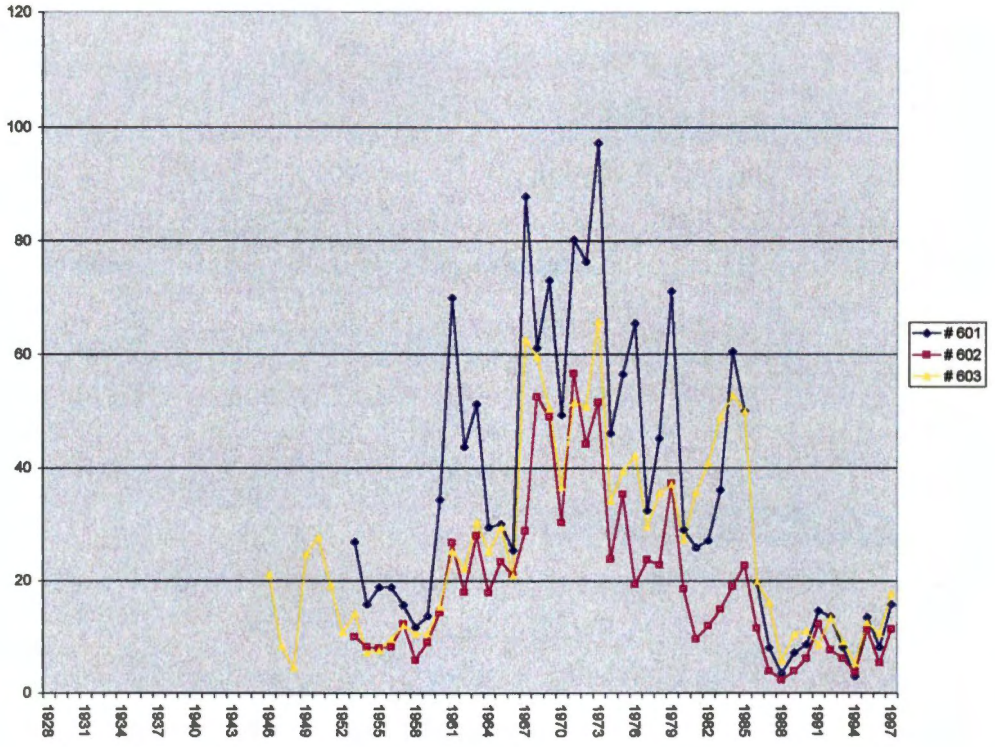


Figure A-1 (continued).



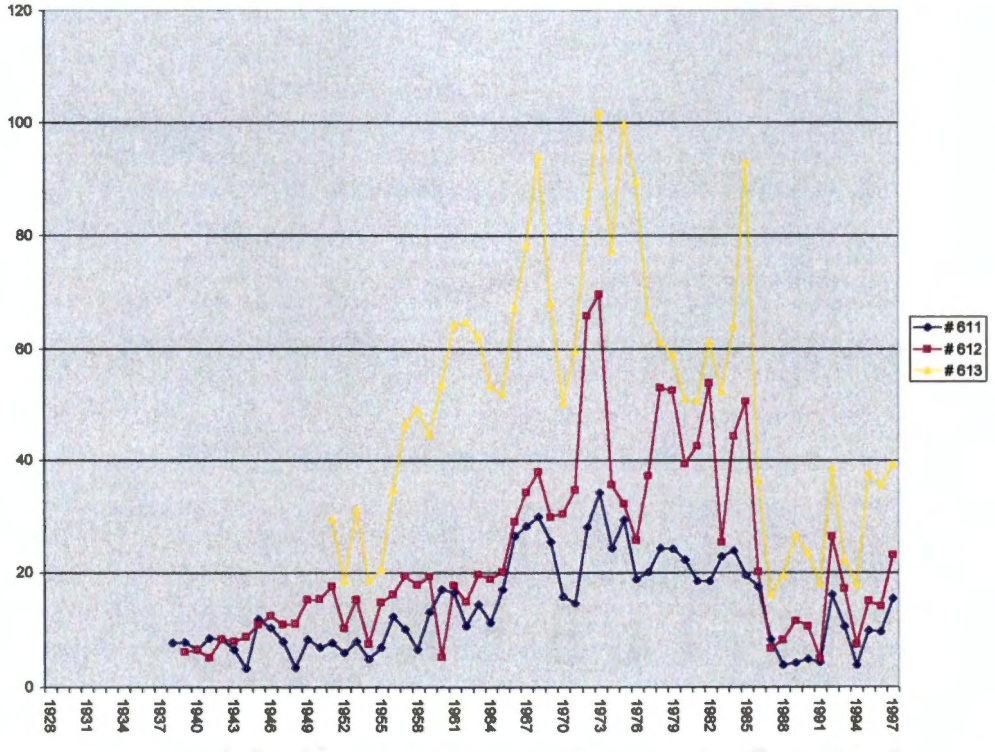
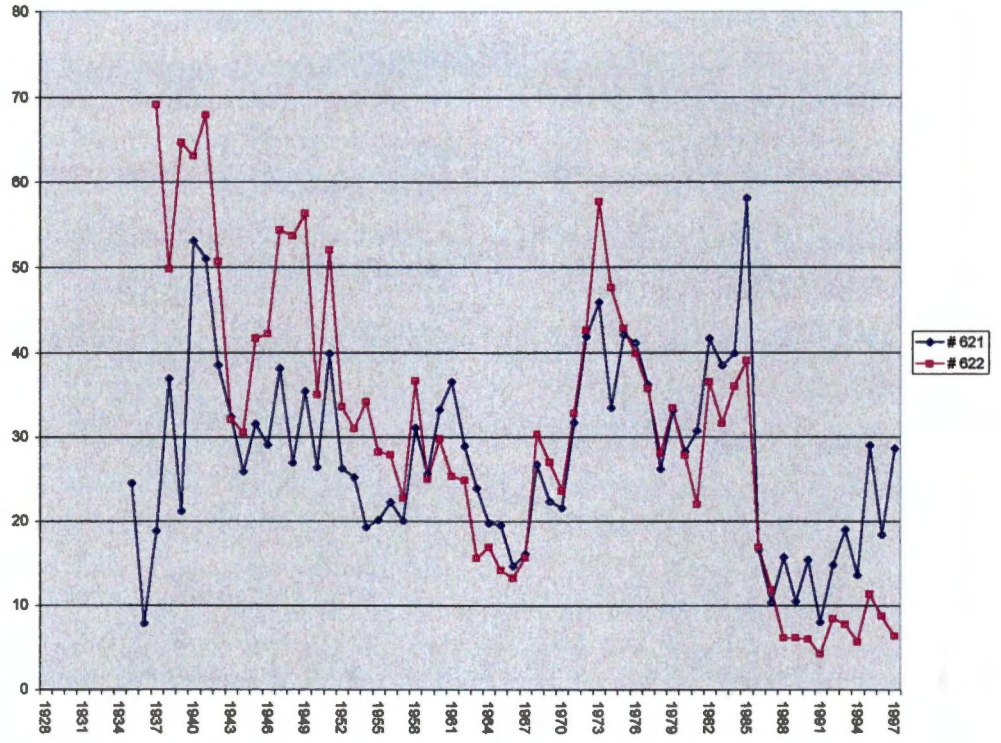


Figure A-1 (continued).



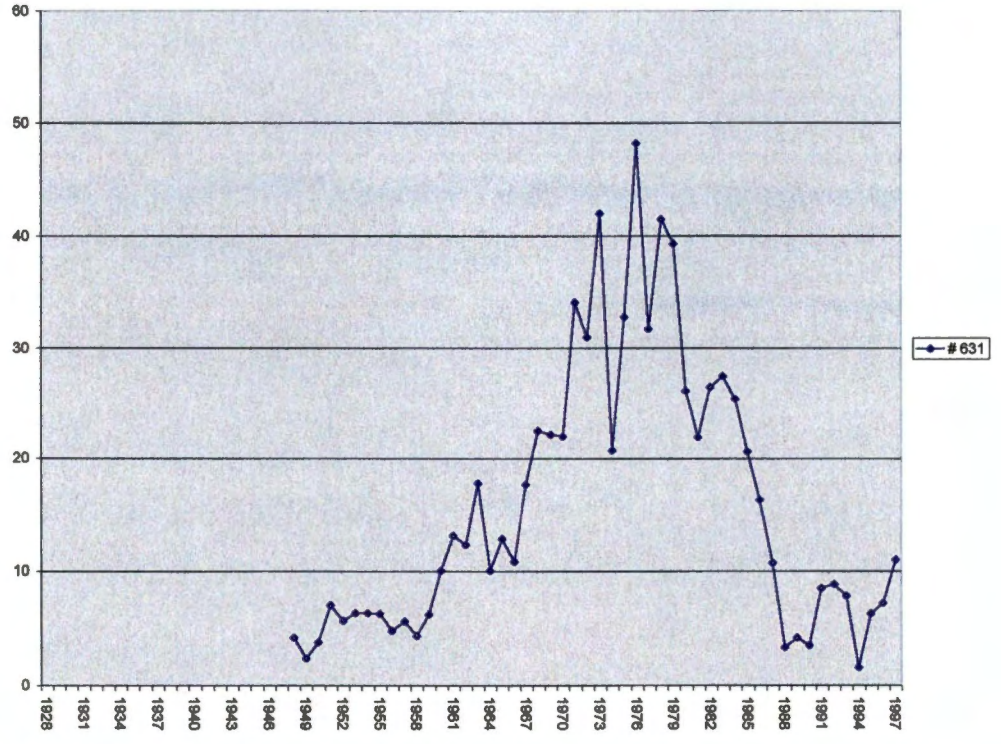
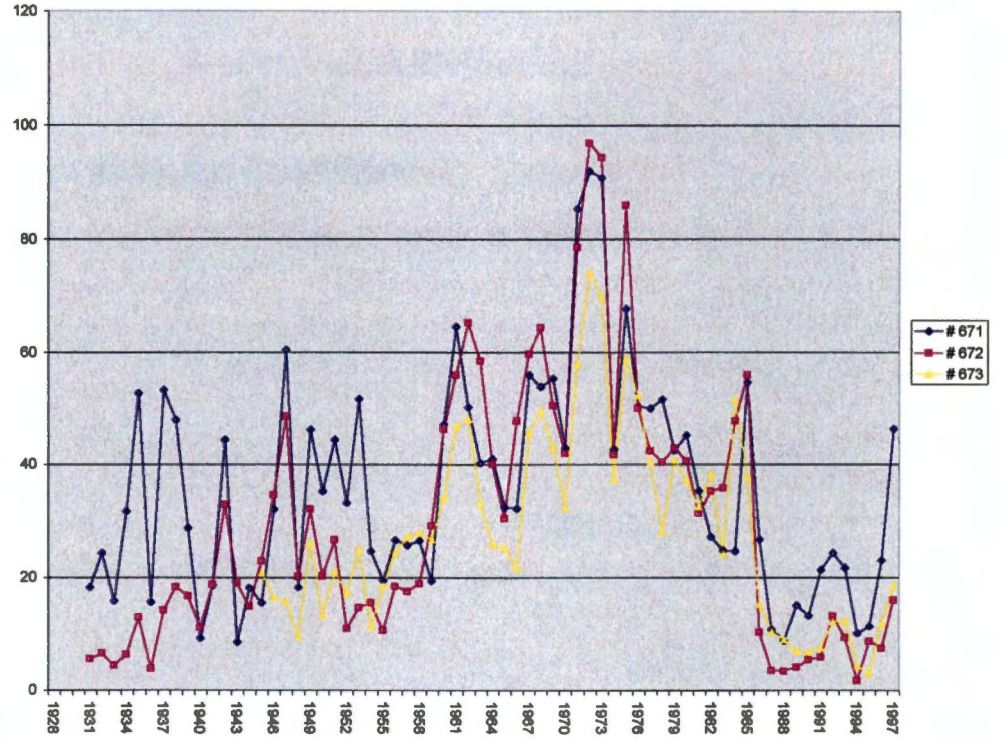


Figure A-1 (continued).



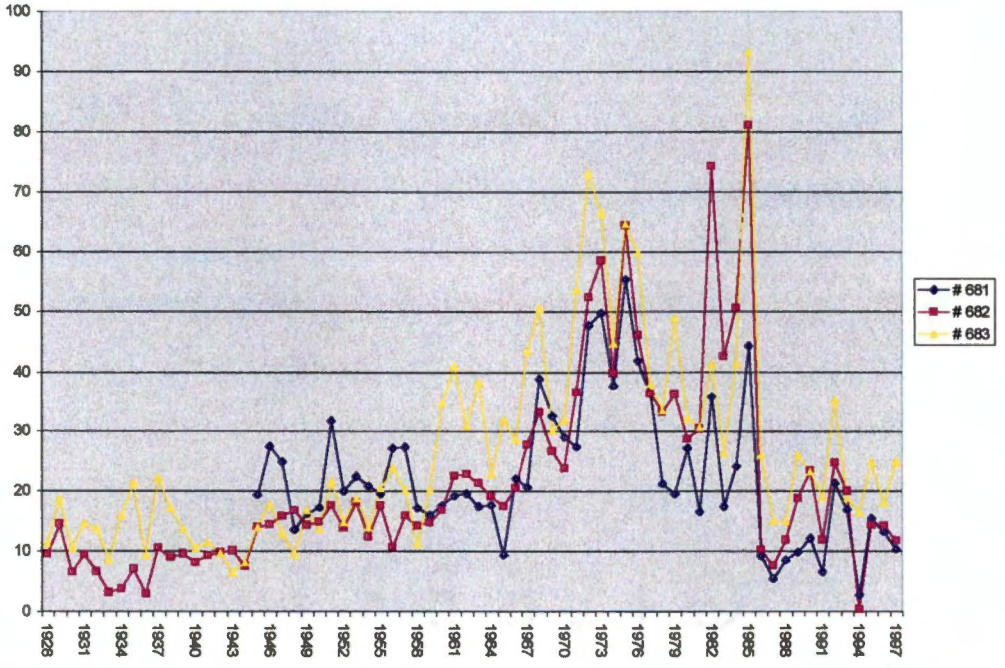


Figure A-1 (continued).

Table A-1. Palmer Drought Severity Index (PDSI) classifications adapted from the National Drought Mitigation Center (1999).

PDSI Value	Moisture Condition
4.0 or more	Extremely Wet
3.0 to 3.99	Very Wet
2.0 to 2.99	Moderately Wet
1.0 to 1.99	Slightly Wet
0.5 to 0.99	Incipient Wet Spell
0.49 to –0.49	Near Normal
-0.5 to –0.99	Incipient Dry Spell
-1.0 to –1.99	Mild Drought
-2.0 to –2.99	Moderate Drought
-3.0 to –3.99	Severe Drought
-4.0 or less	Extreme Drought

Table A-2. Multiple linear regressions used in response function analysis of the WBW Overall population. Tests show the relationship between annual BAI production, within topographic index categories, and monthly climate variables.

Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Overall/Mesic	9.54	<.0001	0.4822
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
nov. temp. past	-3.08	0.0037	0.1115
dec. temp. past	2.70	0.0100	0.0672
jul. temp. present	-4.44	<.0001	0.2505
apr. precip. present	-2.05	0.0471	0.0529
Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Overall/Xeric	8.80	<.0001	0.6185
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
dec. temp. past	2.62	0.0126	0.0351
jul. temp.	-3.89	0.0004	0.3508
aug. precip. past	2.59	0.0137	0.0531
sep. precip. past	2.44	0.0195	0.0152
nov. precip. past	-2.69	0.0107	0.0173
may precip.	3.64	0.0008	0.0867
mar. temp.	-2.45	0.0189	0.0604
Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Overall/Intermediate	10.25	<.0001	0.5000
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
nov. temp. past	-2.92	0.0056	0.0784
dec. temp. past	3.77	0.0005	0.0946
jul. temp.	-3.90	0.0004	0.2336
aug. precip. past	2.77	0.0084	0.0935

Table A-3. Multiple linear regressions used in response function analysis of the WBW Old subpopulation. Tests show the relationship between annual BAI production, within topographic index categories, and monthly climate variables.

Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Old/Mesic	9.45	<.0001	0.4148
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
nov. temp. past	-2.39	0.0215	0.1163
dec. temp. past	2.50	0.0165	0.0774
jul. temp.	-3.89	0.0004	0.2211
Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Old/Xeric	13.18	<.0001	0.4971
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
nov. temp. past	-2.03	0.0465	0.0894
dec. temp. past	2.34	0.0242	0.0536
jul. temp.	-5.31	<.0001	0.3542
Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Old/Intermediate	12.62	<.0001	0.3811
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
dec. temp. past	2.07	0.0444	0.0480
jul. temp.	-4.70	<.0001	0.3331

Table A-4. Multiple linear regressions used in response function analysis of the WBW Young subpopulation. Tests show the relationship between annual BAI production, within topographic index categories, and monthly climate variables.

Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Young/Mesic	12.77	<.0001	0.4893
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
nov. temp. past	-2.43	0.0198	0.1102
dec. temp. past	3.01	1.0045	0.0974
jul. temp.	-4.70	<.0001	0.2817
Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Young/Xeric	8.16	<.0001	0.5696
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
mar. temp.	-2.59	0.0137	0.0002
jul. temp.	-2.75	0.0091	0.3183
sep. precip. past	3.05	0.0042	0.0592
nov. precip. past	-2.91	0.0061	0.0479
may precip.	3.21	0.0028	0.0924
jun. precip.	2.11	0.0421	0.0516
Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Young/Intermediate	12.28	<.0001	0.4795
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
nov. temp. past	-2.52	0.0160	0.1138
dec. temp. past	3.26	0.0023	0.1196
jul. temp.	-4.35	<.0001	0.2461

Table A-5. Multiple linear regressions used in response function analysis of the WBW Overall, WBW Old, and WBW Young mean BAI chronologies. Tests show the relationship between annual BAI production and monthly climate variables. All 106 sample trees are included in the WBW Overall chronology and all trees present in each subpopulation are included in their respective chronologies.

Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Overall	11.93	<.0001	0.4722
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
nov. temp. past	-2.16	0.0371	0.0970
dec. temp. past	2.55	0.0147	0.0698
jul. temp.	-4.81	<.0001	0.3054
Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Old	13.59	<.0001	0.3986
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
dec. temp. past	2.19	0.0345	0.0522
jul. temp.	-4.86	<.0001	0.3464
Dependent Variable	**F Value**	**p-value**	**Model R^2**
WBW Young	12.51	<.0001	0.4840
Independent Variable	**t Value**	**p-value**	**Semi-partial R^2**
nov. temp. past	-2.35	0.0240	0.1063
dec. temp. past	2.86	0.0066	0.0883
jul. temp.	-4.74	<.0001	0.2895

Table A-6. Basal area increment (BAI) statistics for each cored yellow-poplar on Walker Branch Watershed, TN. BAI are given in square centimeters.

Tree #	mean	st.dev.	variance	CV	min	max
11	14.53	9.22	85.05	0.63	0.00	34.30
41	42.75	29.54	872.72	0.69	4.69	112.16
42	39.00	27.33	746.90	0.70	2.91	91.48
43	42.30	22.84	521.61	0.54	6.85	88.04
51	19.22	10.24	104.84	0.53	0.00	38.81
52	15.08	9.39	88.20	0.62	0.00	36.74
53	35.61	20.02	400.62	0.56	2.14	72.31
61	25.01	15.94	254.24	0.64	1.27	58.40
62	20.49	11.99	143.70	0.59	3.21	53.01
63	21.17	18.27	333.93	0.86	0.89	92.68
81	42.20	23.58	556.06	0.56	1.25	100.84
82	36.24	20.71	428.84	0.57	4.98	79.34
91	42.46	31.85	1014.39	0.75	0.00	113.95
101	22.01	16.14	260.61	0.73	1.61	64.68
102	18.96	15.81	249.90	0.83	3.49	64.06
103	15.88	13.10	171.49	0.82	3.10	57.16
121	13.30	8.92	79.49	0.67	0.54	42.91
122	14.88	9.28	86.08	0.62	3.34	44.06
123	13.29	8.96	80.31	0.67	0.00	40.11
131	21.32	12.62	159.35	0.59	3.39	75.80
132	13.69	12.03	144.73	0.88	0.00	68.08
141	13.47	11.06	122.37	0.82	1.47	48.39
151	28.31	13.09	171.23	0.46	4.59	61.77
152	40.38	21.83	476.76	0.54	13.11	95.55
153	45.70	27.50	756.11	0.60	7.78	95.69
161	27.16	16.69	278.45	0.61	2.37	56.62
162	33.84	16.94	287.02	0.50	6.71	69.98
181	24.63	16.54	273.41	0.67	1.29	63.01
182	30.97	23.88	570.26	0.77	0.44	83.36
183	19.01	15.56	242.06	0.82	0.28	56.03
191	32.70	23.18	537.28	0.71	3.09	98.56
192	26.05	19.64	385.64	0.75	3.75	72.08
211	16.46	13.20	174.17	0.80	1.93	52.67
221	14.80	11.98	143.53	0.81	0.00	45.77
241	21.83	18.55	344.19	0.85	0.58	68.16
251	26.43	15.22	231.67	0.58	2.87	68.30
252	14.48	9.87	97.40	0.68	1.14	40.21
253	31.52	14.84	220.08	0.47	7.80	70.55
281	20.24	13.20	174.15	0.65	0.00	55.87
282	15.48	13.85	191.70	0.89	2.07	62.27
283	18.64	12.97	168.30	0.70	2.19	50.15
291	17.65	13.80	190.41	0.78	0.74	51.89
301	31.95	20.50	420.14	0.64	4.53	86.94
311	21.28	14.51	210.45	0.68	3.29	64.23
312	13.69	9.52	90.58	0.70	1.27	37.72
313	25.89	20.15	406.02	0.78	1.60	77.22
331	20.16	15.17	230.00	0.75	0.00	74.99
332	11.88	10.28	105.74	0.87	1.63	43.43
333	18.21	12.93	167.19	0.71	2.87	55.11
341	30.26	18.56	344.51	0.61	8.22	117.51
342	33.24	14.06	197.82	0.42	13.28	62.37
343	16.12	7.47	55.83	0.46	6.33	39.58
351	32.33	20.97	439.75	0.65	0.00	84.65
352	22.82	10.37	107.63	0.45	4.85	44.71
353	19.98	13.82	190.86	0.69	1.47	54.06
361	23.65	14.88	221.52	0.63	0.00	57.09
362	27.41	21.25	451.37	0.78	0.00	108.27

Table A-6 (continued).

Tree #	mean	st.dev.	variance	CV	min	max
371	24.87	20.53	421.66	0.83	0.30	100.18
372	23.91	15.52	240.77	0.65	4.17	71.51
373	18.18	11.93	142.32	0.66	0.00	45.15
401	17.35	8.99	80.76	0.52	0.00	44.39
411	16.60	15.50	240.14	0.93	1.19	64.13
412	20.85	12.62	159.35	0.61	2.40	61.93
413	8.89	7.86	61.79	0.88	0.00	38.60
451	23.41	13.51	182.65	0.58	0.20	54.28
461	20.15	12.33	152.10	0.61	1.88	52.24
462	25.79	14.68	215.64	0.57	3.33	51.52
463	44.79	20.63	425.56	0.46	8.26	84.74
471	14.12	7.80	60.86	0.55	3.22	34.64
472	17.65	10.98	120.61	0.62	1.73	42.97
473	18.78	12.03	144.75	0.64	2.31	46.32
481	15.95	8.47	71.66	0.53	2.15	33.42
482	23.90	13.72	188.15	0.57	5.27	65.82
483	18.64	12.48	155.82	0.67	3.74	58.41
491	17.99	10.81	116.84	0.60	4.16	44.68
492	18.75	11.61	134.83	0.62	2.14	51.62
511	22.02	14.53	211.19	0.66	2.45	59.48
512	26.97	20.40	416.33	0.76	3.05	89.06
513	20.55	11.87	140.82	0.58	2.97	48.86
531	21.04	11.01	121.24	0.52	7.26	59.09
532	20.64	12.22	149.40	0.59	5.65	54.09
533	23.70	13.53	183.16	0.57	1.10	58.46
541	13.86	9.36	87.60	0.68	0.53	41.53
561	15.15	13.02	169.41	0.86	0.29	57.00
562	20.04	14.49	210.01	0.72	3.02	61.01
581	24.62	9.18	84.20	0.37	8.97	50.49
582	31.06	15.25	232.59	0.49	9.03	68.77
583	20.36	12.86	165.32	0.63	3.67	52.71
591	31.85	19.36	374.73	0.61	6.15	76.49
592	29.57	14.71	216.42	0.50	4.37	72.73
593	22.41	12.71	161.49	0.57	1.54	51.86
601	35.58	25.40	645.13	0.71	2.92	97.28
602	19.33	14.29	204.15	0.74	2.35	56.70
603	25.92	16.93	286.63	0.65	4.41	65.80
611	13.95	8.09	65.37	0.58	3.23	34.20
612	22.78	15.83	250.74	0.70	4.93	69.62
613	51.13	23.80	566.66	0.47	16.15	101.81
621	27.95	11.03	121.73	0.39	7.86	58.13
622	31.04	17.13	293.36	0.55	4.26	69.12
631	15.86	12.14	147.36	0.77	1.59	48.19
671	35.83	19.42	377.22	0.54	8.65	91.95
672	29.82	23.19	537.94	0.78	1.74	96.92
673	28.42	17.05	290.56	0.60	2.99	74.10
681	22.62	11.61	134.85	0.51	2.71	55.46
682	21.36	16.59	275.22	0.78	0.42	81.13
683	26.66	17.09	291.91	0.64	6.51	93.17

Table A-7. Data used to characterize each cored yellow-poplar and it's location on Walker Branch Watershed, TN. Crown vigor increases as number increases. Land-use 1 corresponds to older trees and land-use 2 corresponds to younger trees. Soil classes are ranked as follows: 1 is residuum, 2 is colluvium, 3 is recent alluvium, and 4 is ancient alluvium. Topographic location is ranked as follows: 1 is ridge, 2 is southwest aspect, 3 is northeast aspect, and 4 is valley. Topographic index increases as estimated soil moisture level increases.

Tree #	DBH (cm)	crown	land-use	soil class	top. loc.	BA (m^2/ha)	% yp	top. index
11	33.1	1	1	2	4	17.5	25.0	11.45
41	49.7	1	2	4	1	25.0	46.2	6.60
42	48.7	2	2	4	1	22.5	46.2	6.59
43	57.0	3	2	4	1	20.0	46.2	6.91
51	37.8	2	2	4	1	35.0	66.7	8.46
52	33.0	1	2	4	1	30.0	66.7	9.00
53	50.6	3	2	4	1	15.0	66.7	8.62
61	53.1	2	1	4	1	25.0	46.2	8.21
62	47.3	1	1	4	1	30.0	46.2	7.29
63	45.9	1	1	4	1	37.5	46.2	7.29
81	68.4	2	1	2	2	17.5	25.0	7.17
82	51.7	1	1	2	2	27.5	25.0	6.54
91	50.5	1	1	2	2	22.5	14.3	6.66
101	37.6	2	1	2	3	25.0	20.0	6.91
102	35.5	1	1	2	3	32.5	20.0	7.03
103	35.0	1	1	2	3	25.0	20.0	7.22
121	36.4	1	1	1	1	47.5	20.0	6.36
122	40.6	2	1	1	1	40.0	20.0	6.58
123	36.1	1	1	2	1	35.0	20.0	6.64
131	49.2	3	1	3	4	20.0	20.0	12.90
132	38.2	1	1	1	4	30.0	20.0	6.16
141	34.2	1	1	2	2	25.0	14.3	6.53
151	43.6	4	2	3	4	22.5	21.4	11.37
152	45.7	4	2	3	4	22.5	21.4	11.37
153	52.6	4	2	3	4	22.5	21.4	6.13
161	38.3	4	2	2	3	17.5	0.0	7.14
162	41.5	4	2	2	3	27.5	0.0	6.42
181	41.7	2	1	2	2	32.5	20.0	8.77
182	42.6	3	1	2	2	30.0	20.0	6.99
183	37.6	2	1	2	2	35.0	20.0	9.25
191	43.9	2	1	1	3	27.5	22.2	6.62
192	47.5	2	1	2	3	20.0	22.2	8.10
211	40.5	2	1	1	3	25.0	8.3	6.65
221	32.8	1	1	2	2	22.5	10.0	6.61
241	39.7	3	1	1	1	25.0	8.3	5.32
251	42.0	4	2	3	4	15.0	85.7	13.77
252	31.0	3	2	2	4	17.5	85.7	13.37
253	49.3	4	2	3	4	15.0	85.7	13.02
281	40.7	2	1	2	3	17.5	28.6	6.72
282	38.0	2	1	2	3	22.5	28.6	6.44
283	42.1	2	1	2	3	25.0	28.6	6.57

Table A-7 (continued).

Tree #	DBH (cm)	crown	land-use	soil class	location	BA (m^2/ha)	% yp	top. index
291	39.2	2	1	1	2	30.0	0.0	5.62
301	42.9	2	2	2	1	27.5	0.0	6.00
311	44.7	3	1	1	4	25.0	45.5	8.33
312	38.0	2	1	1	4	22.5	45.5	7.53
313	51.2	3	1	1	4	25.0	45.5	7.11
331	49.4	2	1	1	4	27.5	22.2	6.58
332	34.7	1	1	1	4	22.5	22.2	6.58
333	45.2	1	1	1	4	27.5	22.2	9.34
341	48.5	3	2	1	4	20.0	12.5	6.02
342	44.4	4	2	2	4	12.5	12.5	9.72
343	34.4	3	2	2	4	12.5	12.5	9.72
351	56.0	4	1	2	3	27.5	30.0	7.06
352	43.1	3	1	2	3	27.5	30.0	6.70
353	37.4	2	1	1	3	22.5	30.0	6.07
361	47.1	1	2	1	1	27.5	0.0	5.74
362	49.9	2	2	2	1	22.5	0.0	6.90
371	49.3	1	1	2	3	22.5	30.0	8.23
372	47.2	2	1	2	3	22.5	30.0	10.20
373	40.2	1	1	2	3	25.0	30.0	8.77
401	42.7	2	1	1	2	25.0	0.0	10.98
411	40.8	2	1	1	3	25.0	40.0	6.28
412	46.1	2	1	1	3	30.0	40.0	6.34
413	32.1	1	1	1	3	20.0	40.0	6.33
451	34.5	3	1	1	2	20.0	10.0	9.77
461	36.3	2	2	2	1	25.0	33.3	7.06
462	34.3	2	2	2	1	25.0	33.3	7.01
463	45.0	3	2	2	1	22.5	33.3	6.91
471	37.3	2	1	3	4	22.5	0.0	8.62
472	42.3	1	1	1	4	17.5	0.0	8.78
473	38.1	2	1	3	4	15.0	0.0	10.66
481	47.1	2	1	1	2	25.0	9.1	6.67
482	53.4	3	1	1	2	22.5	9.1	6.69
483	41.6	2	1	1	2	25.0	9.1	6.75
491	36.0	3	1	1	1	25.0	0.0	5.74
492	38.7	3	1	1	1	25.0	0.0	5.74
511	39.2	1	1	2	1	35.0	5.0	6.13
512	42.0	1	1	1	1	25.0	5.0	6.24
513	36.5	1	1	2	1	22.5	5.0	6.83
531	48.3	2	1	3	2	20.0	30.0	11.49
532	45.5	1	1	1	2	25.0	30.0	6.45
533	47.3	2	1	1	2	17.5	30.0	11.83
541	37.1	2	1	2	3	30.0	0.0	7.83
561	40.0	1	1	1	1	32.5	14.3	6.37
562	41.0	2	1	2	1	35.0	14.3	6.44
581	48.9	2	1	3	4	22.5	18.2	9.55
582	50.5	2	1	3	4	22.5	18.2	9.15
583	45.6	2	1	3	4	17.5	18.2	13.86

Table A-7 (continued).

Tree #	DBH (cm)	crown	land-use	soil class	location	BA (m^2/ha)	% yp	top. index
591	51.7	2	2	1	3	27.5	18.2	7.87
592	49.5	3	2	1	3	15.0	18.2	6.94
593	41.9	3	2	1	3	25.0	18.2	6.52
601	51.5	2	2	1	1	25.0	30.0	5.84
602	38.8	2	2	1	1	30.0	30.0	6.05
603	44.7	3	2	1	1	17.5	30.0	6.60
611	34.7	2	2	1	3	30.0	27.3	7.48
612	43.5	3	2	2	3	27.5	27.3	6.31
613	63.0	3	2	1	3	25.0	27.3	6.33
621	51.9	3	1	1	1	22.5	42.9	13.64
622	57.3	3	1	1	1	15.0	42.9	11.08
631	33.4	2	1	1	1	15.0	0.0	5.52
671	65.3	1	1	2	3	30.0	50.0	5.92
672	58.2	1	1	2	3	22.5	50.0	5.98
673	48.0	1	1	2	3	22.5	50.0	6.55
681	44.8	2	1	3	4	30.0	37.5	14.46
682	46.9	1	1	1	4	22.5	37.5	7.03
683	54.2	2	1	1	4	22.5	37.5	6.31

Table A-8. Coordinate, direction, and distance data used to locate the postion of each cored yellow-poplar on Walker Branch Watershed, TN.

Tree #	North gridline	East gridline	azimuth	distance (m)
11	8186	9694	199	6.3
41	7658	7054	32	11.0
42	7658	7054	69	2.7
43	7658	7054	101	15.9
51	7658	7318	25	8.9
52	7658	7318	100	5.5
53	7658	7318	157	12.7
61	7658	7582	154	11.1
62	7658	7582	279	11.7
63	7658	7582	302	11.4
81	8186	9430	115	19.6
82	8186	9430	322	5.5
91	8186	9430	133	14.1
101	8186	8902	129	11.5
102	8186	8902	144	13.7
103	8186	8902	174	10.7
121	7658	7846	42	8.1
122	7658	7846	53	6.4
123	7658	7846	321	8.3
131	7658	8110	16	14.8
132	7658	8110	109	5.2
141	7658	8374	169	9.5
151	7130	8374	41	14.3
152	7130	8374	63	14.5
153	7130	8374	337	12.8
161	7130	8110	20	15.0
162	7130	8110	330	15.2
181	7130	7582	21	9.8
182	7130	7582	35	3.6
183	7130	7582	292	13.8
191	7130	7318	270	13.9
192	7130	7318	334	17.7
211	7130	6790	7	8.8
221	6602	6790	19	14.5
241	6602	7054	48	5.0
251	7130	5470	110	8.1
252	7130	5470	146	8.9
253	7130	5470	219	18.6
281	6074	6526	28	17.3
282	6074	6526	59	5.2
283	6074	6526	200	6.5
291	6074	6790	237	14.5
301	6074	7054	99	19.1
311	5446	7054	43	13.4
312	5446	7054	14	10.1
313	5446	7054	326	7.6
331	7130	5998	126	18.4
332	7130	5998	136	10.6
333	7130	5998	309	9.5
341	7130	5734	74	11.1
342	7130	5734	145	18.0
343	7130	5734	147	18.0
351	6602	5734	93	16.4
352	6602	5734	104	10.4
353	6602	5734	185	6.3
361	6602	5470	357	17.0
362	6602	5470	29	18.1
371	6602	5998	22	14.1

Table A-8 (continued).

Tree #	North gridline	East gridline	azimuth	distance (m)
372	6602	5998	60	10.8
373	6602	5998	102	16.3
401	7658	8902	304	20.0
411	7658	8638	235	6.4
412	7658	8638	245	12.0
413	7658	8638	280	2.5
451	7130	9430	115	7.6
461	6074	7318	115	9.2
462	6074	7318	220	14.5
463	6074	7318	235	18.0
471	5546	7318	327	15.1
472	5546	7318	340	20.6
473	5546	7318	345	17.3
481	5546	7582	147	19.1
482	5546	7582	168	9.5
483	5546	7582	216	19.1
491	6602	8374	123	21.3
492	6602	8374	126	21.6
511	5546	8374	7	10.0
512	5546	8374	257	206.0
513	5546	8374	269	10.5
531	5546	7846	193	6.8
532	5546	7846	227	20.3
533	5546	7846	231	14.3
541	7130	6262	343	13.2
561	6074	8638	354	18.5
562	6074	8638	141	11.9
581	6074	7846	45	7.0
582	6074	7846	92	10.5
583	6074	7846	166	15.5
591	6074	7582	349	8.9
592	6074	7582	87	19.7
593	6074	7582	155	9.1
601	6602	7582	352	10.7
602	6602	7582	19	3.2
603	6602	7582	146	7.6
611	6602	7846	343	13.0
612	6602	7846	67	10.8
613	6602	7846	249	15.4
621	6602	8110	327	4.8
622	6602	8110	339	8.8
631	6602	8638	65	19.9
671	6602	6262	359	9.8
672	6602	6262	40	11.3
673	6602	6262	209	10.7
681	6602	6526	20	14.4
682	6602	6526	114	13.8
683	6602	6526	260	12.7

Table A-9. BAI statistics for categories of Walker Branch Watershed yellow-poplars. Statistics were examined to rank or validate the appropriateness of assigned ranks to categorical variables used in regression analysis.

Variable	Descriptive Statistic						
Land-use	**Mean**	**Median**	**Variance**	**CV**	**Min**	**Max**	**Range**
1-Old	21.5	20.5	45.3	31.3	8.9	42.5	33.6
2-Young	29.6	28.9	95.6	33.0	13.9	54.1	37.2
Soil Class	**Mean**	**Median**	**Variance**	**CV**	**Min**	**Max**	**Range**
1-Residuum	21.7	20.4	57.8	35.0	8.9	51.1	42.2
2-Colluvium	24.5	22.8	71.9	34.6	13.3	44.8	31.5
3-Anc. Alluvium	26.6	24.6	78.0	33.2	14.1	45.7	31.6
4-Mod. Alluvium	29.0	25	118.6	37.6	15.1	42.8	27.7
Crown Vigor	**Mean**	**Median**	**Variance**	**CV**	**Min**	**Max**	**Range**
1-Poor	21.3	19.7	77.2	41.1	8.9	42.8	33.9
2-Fair	22.3	20.2	46.3	30.6	13.7	42.2	28.5
3-Good	27.1	23.9	84.3	33.9	14.4	51.1	36.6
4-Excellent	33.2	32.3	39.7	19.0	26.4	45.7	19.2
Top. Location	**Mean**	**Median**	**Variance**	**CV**	**Min**	**Max**	**Range**
1-Ridge	24.8	21.9	79.5	35.9	13.3	44.8	31.5
2-SW slope	23.9	21.0	80.6	37.6	13.5	42.5	29.0
3-NE slope	23.8	22.6	72.3	35.7	8.9	51.1	42.2
4-Valley	23.1	21.3	70.6	36.3	11.9	45.7	33.8

VITA

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