

**Using Dendrochronology to Help Predict Effects  
Of Global Climate Change on East Texas Forests**

**FINAL REPORT**

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## INTRODUCTION

Anthropogenically induced changes in global climate over the course of the next century are projected to substantially impact vegetation (Smith and Tirpack 1990).

Predicting resultant changes in vegetation composition and structure is therefore an important goal of plant community ecology (Woodward and Cramer 1996).

Dendrochronology, i.e. the science of tree ring analysis (see Fritts 1976, Fritts and Swetnam 1989), can provide critical information for developing predictions for forest and savanna habitats. In particular, dendrochronology provides direct evidence concerning species and genus level differences in responses of forest trees to climatic variation. This type of information is useful for modelers attempting to make quantitative predictions about climate effects on forests (Shugart 1984, Kobe 1996). Dendrochronological studies conducted across geographic or climatic gradients, particularly near the range limits of species, are likely to be particularly useful for predicting shifts in forest composition in response to changes in regional climates (Graumlich 1989, Huntley et al. 1989).

In addition to data pertaining to climatic effects on tree growth, dendrochronology can also provide important evidence concerning historical patterns of forest disturbance (e.g. Glitzenstein et al. 1986, Lorimer and Frelich 1989, Nowacki and Abrams 1997). These two variables are not necessarily unrelated, since climate patterns can influence patterns of canopy disturbance and regeneration (Clark 1990, Bessie and Johnson 1995).

Herein we report on a dendrochronological study of forest vegetation of the west Gulf Coastal Plain. This region is located at the westernmost edge of the eastern deciduous forest/southern evergreen forest (Braun 1950, Kuchler 1964), and is therefore likely to be particularly vulnerable to projected increases in drought. The report consists of two main sections. The first section consists of an analysis of tree growth using the

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ARSTAN (autoregressive standardized) transformation (see Cook 1985); this transformation, used widely in dendroclimatic analyses (Cook and Kariukstis 1990), emphasizes short-term (i.e. year-to-year) variation in tree growth and tends to filter out longer term trends or pulses related to disturbance phenomena and/or tree physiology. For our purposes, the main advantage of transforming the data in this way is that we are then able to directly examine differences among species in climate responses without fear of complications or confounding due to other influences on tree growth.

The second section of the report contains an analysis of regional forest disturbance history using the "percent growth change" transformation recently described by Nowacki and Abrams (1997). This transformation is a type of "low pass filter" (sensu Fritts 1976) designed to filter out short-term variation and focus on substantial and prolonged increases and decreases in diameter growth, i.e. the sort of variability most likely to be removed by ARSTAN. In theory, this sort of transformation should remove most climatic influences, leaving only a "disturbance" signal. In practice, however, unusually prolonged droughts or other climatically stressful periods (e.g. freezing weather in colder regions) might also be detected in these growth change chronologies (Nowacki and Abrams 1997).

## METHODS

Tree cores were obtained from 38 stands distributed from western Louisiana to central Texas (Figure 1). Stands were located within a 300 km x 100 km transect positioned so as to cross the range limits of as many eastern forest tree species as possible. The transect also spanned a distinct climate gradient, from moister and slightly

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cooler in the east to hotter and drier in the west (Figure 2). Most of the selected stands were considered mature and free of recent human disturbance. In some cases stands had been described as old-growth (Mohler 1979, Orzell 1990, Martin and Smith 1991, 1993). A particular effort was made to include sites on or near the range limits of the various species, though some of these stands had evidence of more recent anthropogenic disturbance.

When sampling a stand, the general procedure was to core 10-15 large or old-looking trees of each pine, oak or beech species which might be present in the stand. Typically, we would start from a given point and core the first 10-15 trees which we encountered which met these rather broad criteria. A different procedure, similar to that employed by Lorimer and Frelich (1989) was used in the case of four sites thought to be at or near old growth. In these stands a 20 m x 50 m transect was laid out and thirty random points were selected from within the transect. We then cored the nearest tree to each point. Chronologies were then developed for each species for which sufficient numbers of individuals were cored to allow for cross-dating. Lorimer and Frelich (1989) maintain that such a sampling scheme allows a more direct conversion from release frequencies into estimates of percent canopy disturbed.

Cores were processed in the laboratory and tree rings measured and cross dated using standard dendrochronological procedures (see Fritts and Swetnam 1989). Cores and tree-ring data are stored at the Tree-Ring Laboratory, Palisades, NY; a copy of the data are in the office of J.S. Glitzenstein, Charleston, SC.

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Arstan Analyses

The ARSTAN program is described in detail in Cook (1985). The program removes long-term trends and autocorrelation from tree-ring series, leaving only short-term variation due to climate and "white noise" (i.e. random error).

Following processing with ARSTAN, the resultant tree-ring chronologies were subjected to rotated principal components analysis (see e.g. Richman 1986). RPCA is a multivariate technique which attempts to reduce multiple sources of variation (e.g. the individual tree-ring chronologies) into a few dominant modes or factors which can then be interpreted by comparison with the original data or other sources of information. An initial RPCA included all sites and species (a total of 99 chronologies). Subsequently the analysis was repeated for various subgroupings of the data to completely explore differences suggested by the initial run. Tree-ring data included in the analysis encompassed the period 1941-1993, a time period common to all chronologies.

As will be discussed below, the results of the RPCA essentially indicated that the dominant sources of variation in the tree-ring indices were related to phylogenetic differences among a few major groups of species. These groupings apparently reflected differences among species in characteristic responses to climate. To identify these responses, individual tree-ring chronologies were correlated with a series of climate variables including mean monthly temperature and precipitation data for the 17 month period including and prior to the year in question. The resulting correlation coefficients, or response functions (Blasing et al. 1984), were then averaged across species groups, as identified by the RPCA. This entire analysis was repeated twice, once for the cooler,

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wetter part of the transect (located east of 94.5 degrees longitude), and again for the warmer, drier part of the transect (located west of this longitudinal division). Climate data used in these analyses were averages of individual weather stations located within the two study areas.

In a final analysis, the correlation coefficients described in the previous paragraph were themselves used as input for a final RPCA. If differences in climate responses form the basis of the phylogenetic effect detected in the tree-ring RPCA, then an RPCA based on climatic correlations should produce essentially the same patterns. This final RPCA analysis therefore formed a rather strong test of the hypothesis that tree species differ in climate responses and that these differences allow us to differentiate "functional groups" of trees (sensu Woodward and Cramer 1996; i.e. trees with related and characteristic responses to climate changes).

### Disturbance History

Percent growth change (i.e. disturbance history) chronologies are constructed as follows (Nowacki and Abrams 1997; see also Glitzenstein et al. 1986 for a not too dissimilar approach). For each year one obtains two averages: (1) the average radial growth over the preceding nine years plus the year in question (R1), and (2) the average growth over the subsequent decade (R2). The difference between these two periods (R2-R1) is then expressed as a percentage (i.e. of the growth during R1), referred to as a percent growth change. Large positive values indicate sustained growth increases associated with releases from competition by canopy disturbance events or, perhaps, by

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prolonged periods of favorable climate. Large negative values can indicate sudden suppression due to increasing competition, effects of unusually prolonged droughts or defoliation, or direct negative effects of disturbance (e.g. physical damage). Based on comparisons of stands with known logging histories, Nowacki and Abrams (1997) concluded that positive GC pulses at or near 100% represent "catastrophic disturbance", i.e. nearly complete canopy removal, whereas lower GC pulses are roughly proportional to the amount of gap area.

Because a percent growth change chronology potentially includes information about both climate and disturbance, a further procedure is necessary to separate the two signals. One approach to this problem (Nowacki and Abrams 1997) is to transform the Palmer Drought Severity Index (PDSI; Palmer 1965) in an analogous fashion as the tree ring data, so as to filter out short-term variability and emphasize sustained increases or decreases in drought. The growth change chronology is then regressed on the transformed PDSI chronology (referred to as a PDSI difference chronology). If the regression is significant it is then used to predict the maximum growth change that might be accounted for by climate; typically this quantity is estimated as that growth change associated with the maximum value of the transformed PDSI. Growth change values above this level are considered indicative of "releases" due to canopy disturbance. If the climate/growth regression is not significant a default cutoff of 25% is used as the threshold for release detection.

In this study summer (June - September) PDSI data were used to calculate PDSI difference chronologies used in the climate-growth regressions. These data were used because they were readily available to one of the authors (E.R. Cook); results will need to

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be checked using other PDSI measures (e.g. Nowacki and Abrams 1997 used average annual PDSI). Summer PDSI data used herein were obtained from a grid of such data interpolated from the actual NOAA weather station recordings. For each stand we used PDSI data from the grid point closest to that stand.

Nowacki and Abrams (1997) ignored severe growth depressions, since their interest was in reconstructing releases. However, in the current study, where we are interested as well in negative effects of disturbance and competition, we will also recognize "suppressions", defined as growth change values below the cutoff likely explainable by climatic variation. As in Nowacki and Abrams (1997), overall (i.e. summarizing across stands) release or suppression chronologies will be constructed by tabulating dates of release or suppression "peaks", where a peak is defined as the single highest (or, in the case of suppressions, lowest) value in a series of values exceeding (or, in the case of suppressions, falling beneath) the climate cutoff.

Our goals in the present study differ from those of Nowacki and Abrams (1997) in another way as well. Whereas Nowacki and Abrams (1997) were interested exclusively in disturbance history, we are also interested in the other source of variation in growth change chronologies, i.e. prolonged periods of climatic favorability or unfavorability which might substantially impact forests. Effects of such episodes might be expected to show up more clearly in growth change chronologies than in ARSTAN where they might be filtered out as autocorrelation (i.e. "persistence"). Thus the regression analyses of growth change chronologies vs. transformed PDSI chronologies are of interest not only as an aid in filtering out climate effects, but also for any information they may contain about effects of major climate "shocks" on tree growth. Furthermore, geographic patterns in climate

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correlations may indicate shifts in the relative effect of climate effects vs. competition and disturbance.

Finally, we subjected the growth change chronologies to RPCA using methods similar to those employed for the ARSTAN chronologies discussed in the previous section. The main difference is that thus far only an initial overall analysis has been performed and we have not yet carried out analyses of subgroupings of the data. Also, Rule-N was not used in determining which factors to save for rotation; instead, all factors with eigenvalues  $> 5$  were retained in the analysis. Growth change (henceforth GC) chronologies used in the RPCA analysis encompassed the period 1930-1983; this shift was necessary because, as described above, GC values cannot be calculated for the last decade of the original unmodified chronology. It should be remembered, however, that, since each GC value compares the average of the preceding and subsequent decade, a GC chronology spanning the period 1930-1983 actually contains information about the period 1920-1993. Due to the requirement for longer chronology lengths, only 85 chronologies were included in the disturbance history RPCA, as compared to the 99 used in the ARSTAN analysis.

Results of the GC RPCA were interpreted on the basis of ANOVA and regression analysis of the factor loadings. Factor loadings (i.e. of individual chronologies) were classified by sites, species, and community types (i.e. as defined by Marks and Harcombe 1981). Classification into community types was based on species composition. In most cases the classification was straightforward; however, in far western stands where diagnostic species were absent it was necessary to place greater reliance on soils and landscape position when assigning a stand to a particular type of community. Regression analysis was used to test for effects of geography; latitude and longitude were the two

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independent variables included in the analysis.

**RESULTS AND DISCUSSION****ARSTAN-Related Analyses**

The RPCA of the ARSTAN-transformed chronologies included four significant factors (according to Rule-N), collectively explaining about 54% of the total variance. Following varimax rotation, these four factors accounted for 16.1, 18.9, 12.6 and 6.4 percent of the total variation, respectively.

Factor loadings of individual chronologies, classified by site and species, are displayed graphically in Figures 3-4. The most obvious pattern relates to clustering of groups of evolutionarily related groups of species. Factor 1 tends to separate species in the black oak subgenus (high factor 1 loadings) from other species groups, including pines and oaks in the white oak subgenus (low factor 1 scores). Factor 2 shows an even cleaner separation, distinguishing the three pine species (high factor 2 scores) from hardwoods in general. Beech tends generally to cluster with white oaks along the first two PCA axes. However, beech is separated from white oaks along Factor 3. Factor 4 is difficult to interpret and may reflect some effect of site type. Even if this were true, however, site effects would still be minor when compared to the effect of phylogeny.

The above patterns are summarized concisely in the form of a series of box plots (Figure 5). Results are displayed separately for eastern and western sites. The dividing line is the 94 degree, 30 minute meridian, chosen because it corresponds to a significant jump

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in temperatures and, presumably drought stress. The most obvious geographical effect is the considerable overlap between factor #1 loadings of the oak subgenera in the droughtier western part of the study area, which contrasts with the relatively clean separation in the moister eastern section. It appears that tendencies towards climatic specialization by the oak subgenera may be overridden under more stressful, limiting climatic conditions.

One problem with the full analysis, described above, is that not all species or groups of species were present at all sites, possibly resulting in some confounding of the results. To check for confounding the analysis was repeated with only those sites included which had at least three of the four phylogenetically related groups of trees. The major difference between this revised analysis and the full site analysis was the disappearance of factor 4, i.e. the factor perhaps attributable to site effects. The most likely explanation is that the existence of this factor was due to effects of one or two sites not included in the "common site" analysis.

The RPCA was also repeated for various other subgroupings in order to check for differences within these subgroupings which might have been hidden by the full analysis. For the most part these additional tests tended to support the full analysis and did not reveal further significant subgroups.

The RPCA analyses described above provided strong evidence for a "phylogenetic effect" on tree ring chronologies. The obvious next question concerned differences in climate responses among these phylogenetically defined species groups. To investigate this question the 99 tree ring chronologies were each correlated with regional precipitation and temperature records to produce climate correlation functions (Blasing et al. 1984).

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This analysis was repeated for the eastern and western sections of the study area.

Results for the two sections (Figures 6-7) were reasonably consistent with regards to responses of the different species groups, the main difference between the two areas being in the strength of the climate correlations. As might be expected, the correlations were generally greater in the drier western section than in the less climatically stressful eastern section of the study area.

Climate responses of the different groups (Figures 6-7) can be summarized as follows. Black oak, and, to a lesser extent, white oak growth appeared to be particularly responsive to variability in precipitation early in the growing season (i.e. April and June). In contrast, pines were most sensitive to late summer precipitation (June and August in particular). Growth of beech was most highly correlated with May precipitation. All four groups demonstrated a pronounced inverse correlation with growing season temperatures, during June through August. The strongest evidence for preconditioning was for black oaks and pines for both precipitation and temperature during the prior growing season.

The final RPCA, in which climate correlations with individual tree-ring series formed the input data, independently confirmed the climatic basis of the "phylogenetic effect" identified in the RPCA of ARSTAN derived tree-ring indices. Results from this analysis, separated the various species groups in a manner very similar to the results based on tree-ring indices alone (Figure 8). Associated factor scores (right side of Figure 8) suggested that pine species were favored particularly by cool/wet conditions from the prior November to the current September (i.e. in the year of the particular ring under consideration) and warm/dry conditions in the prior June-August. Unlike the pines, hardwood species appeared to be favored by cool and wet conditions in the previous year as well as in the

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current year. The main distinction among the hardwoods included in the study was between white oaks and black oaks. Both oak groups had similar climate requirements; however, black oaks appeared to benefit from cooler wetter conditions somewhat later in the growing season.

The identification of a phylogenetic effect in tree ring chronologies is relevant to the identification of functional groups (sensu Woodward and Cramer 1996) for predicting effects of climate change on forests. Unlike previous approaches for identifying functional groups, our analyses allow us to base these groupings directly on tree responses to climate variation. In contrast to prior ideas, the ARSTAN-related analyses suggest that evolutionary relationships rather than ecological relationships may be the best predictors of tree responses to global climate changes.

Percent Growth Change Analyses

*Tests of the method:* Growth change chronologies for all species and stands are presented in Appendix A, arranged alphabetically, by stand. Two of these are of particular interest in that they allow tests of the Nowacki and Abrams (1997) method of reconstructing disturbance history. We begin with those chronologies obtained from the Beech Creek Unit, Big Thicket National Preserve. This site was the subject of an exceptionally thorough study of land use history (Wilson 1979). She reconstructed three periods of elevated disturbance in the southwestern section of BCU where we collected our cores. First, and probably most severe, was the original logging of the site in 1928-1929. This disturbance shows up clearly in the beech and white oak chronologies, the two chronologies old

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enough to include many trees originating prior to the disturbance. Loblolly pine also shows a GC peak around this time, but the peak is lagged somewhat behind beech and oak, probably because the pines were young, originating at the time of the disturbance or shortly before. The other two chronologies, for water oak and southern red oak, are too young to check for indications of this disturbance.

In addition to the original logging, a second, probably less severe, cutting took place in the mid 1950's (Wilson 1979). This cutting is also associated with GC peaks in each of the chronologies, generally lagged by a few years after the disturbance. Another possible cause for these particular GC peaks is recovery from, or disturbance associated with, severe drought during the mid 1950's. A final disturbance reconstructed by Wilson (1979) was widespread decline of loblolly pine associated with pine bark beetle (*Dendroctonus frontalis*) outbreak during the mid 1970's. This recent disturbance is reflected in all chronologies except white oak. In the case of loblolly pine, the beetle outbreak appears as a distinct growth suppression (i.e. a growth decline more severe than that predicted by climate) suggesting that loblolly pine trees at the site may have been attacked but survived the infestation. As would be expected, the hardwood species showed positive responses to the beetle outbreak indicating release from competition.

A second check on the method was provided by longleaf cores collected at the Rice University permanent study plot at the Turkey Creek Unit of the Big Thicket National Preserve (Turkey Creek Plot chronology shown in Appendix A on page labeled Longleaf Pine Sites-1). Based on age structure analyses, as well as tree-ring chronologies, we had previously identified a severe canopy disturbance at this site occurring in 1929 (Harcombe et al. 1993). Based on Wilson's (1979) findings, the rather close proximity of TCU and

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BCU, and conversations with local people, it appeared that the 1929 disturbance at TC represented the initial logging of the site. This severe disturbance shows up clearly in the longleaf GC chronology presented herein even though the cores included in the present chronology were not the same ones used in the earlier study.

Sapling age structure analysis and a few disks cut from living and dead trees suggested that the TC site had burned at least once in the mid 1950's and perhaps again in the early 1960's (Harcombe et al. 1993). In upland forests in the south fires are generally too cool to cause extensive canopy mortality and the effect of fire on longleaf pine trees is primarily to scorch needles and thereby restrict growth (Wahlenberg 1946, Glitzenstein et al. 1995). In the Turkey Creek Plot GC chronology the effect of fire appears to show up as a rather prolonged growth decline during the late 1950's and early 1960's which on several occasions drops below the lower threshold predicted on the basis of climate.

A further investigation of fire effects on growth was attempted through analysis of longleaf cores from a site directly adjacent to the TC PSP; this site (Turkey Creek Fire chronology in Appendix A, Longleaf Sites I) was separated from the PSP only by a bay forest and intermittent creek and was very similar in most respects to the PSP. The main differences between the two areas was in recent fire history; fire has been excluded from the PSP since at least 1980 (i.e. the beginning of the long-term study). In contrast, Big Thicket Preserve had conducted several prescribed burns during this period in the surrounding upland areas.

A visual comparison of these two GC chronologies (TCP and TCF) indicated very similar growth patterns throughout most of the history of the two sites, and this

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Impression was corroborated by a statistical comparison ( $r = 0.95$  for the period 1930 - 1983). Note in particular the identical release peaks due to logging in 1929 and the similar response to presumed fires during the 1950's-1960's. The only real discrepancy between the two chronologies is in recent years. Whereas the TCF chronology indicates few recent growth extremes, the TCF chronology shows continued growth declines. It appears that the effect of the repeated prescribed fires has been to accentuate effects of earlier wildfires, resulting in long-term growth depression in these trees. Similar prolonged growth declines in other longleaf chronologies may also indicate periods with frequent fires. In the absence of other information about stand history, it may, however, be difficult to separate such effects of frequent burning from growth declines due to other causes, e.g. increasing hardwood competition due to prolonged fire exclusion.

In summary, the checks on the Nowacki and Abrams (1997) method presented herein suggest that it can be applied in Big Thicket forests. The method is especially useful for reconstructing periods of release following canopy disturbance, which was the main goal of its developers (Nowacki and Abrams 1997). Furthermore, the method also appears to provide some indications of direct negative effects of disturbance, e.g. declines in loblolly growth due to beetle infestations and declines in longleaf growth due to crown scorch from surface fires. Results presented below suggest, however, that the Nowacki and Abrams (1997) method is not entirely effective at filtering out effects of prolonged and severe droughts, effects which can mimic those of certain types of disturbances.

*Old Growth Stands:* Despite centuries of Spanish rule, east Texas was essentially "virgin" territory prior to around 1850 (Wilson 1979, Frost 1993). Thus stands containing

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appreciable numbers of trees predating this date can be used to reconstruct presettlement disturbance history. Three of our stands met this criterion: (1) San Augustine Savanna (labeled as such in Appendix A; referred to here as SAS; located in Sabine National Forest, San Augustine County, TX) contained many old post oaks (*Quercus stellata*; 8 of 14 trees in the chronology older than 1800). (2) Champion Longleaf (CL; owned by Champion Timber Company, located in Polk County Texas; chronology presented in Longleaf Sites I, Appendix A) included 5 of 17 longleaf pine (*Pinus palustris*) trees predating 1850. (3) An 800 yr old cypress stand (*Taxodium distichum*) from Peach Tree Point, Nechos Bottom Unit, Big Thicket National Preserve. The present discussion will deal with the first two of these stands only.

Pre-1850 disturbance histories of the SAS and CL stands were relatively similar, as indicated by the two old chronologies. Prior to this date, neither stand showed evidence of "catastrophic" canopy disturbance (i.e. average GC values near or greater than 100%). On several occasions the SAS QUST chronology indicated mild disturbances barely exceeding the cutoff attributable to climate. These were interspersed with periods of growth decline, several of which fell below the climate cutoff. Similar GC chronologies for post oak in Pennsylvania were interpreted by Nowacki and Abrams (1997) as indicative of periodic moderate intensity fires, possibly set by Native Americans. According to the post oak chronology, the disturbance history of SAS post-1850 was not greatly different than pre-1850. The most distinctive difference was a relatively prolonged period without appreciable disturbance lasting from around 1920 through 1960. This hiatus in disturbance was also detected in the Nowacki and Abrams (1997) chronologies, which showed definite reductions in disturbance frequency during the present century. This period of low recent

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disturbance was interrupted in 1960 by the most severe disturbance of the entire chronology, exceeding a GC of 50%. It is possible that this disturbance was associated with more than ordinarily severe wildfires resulting from the 1950's drought and decades of accumulated fuels.

The SAS post oak chronology suggests little evidence of major anthropogenic disturbance; however, this conclusion is not consistent with other chronologies from this site. *Pinus echinata*, in particular, indicated a major release peak during the 1940's. The relatively young ages of the pines also suggest a history of selective logging. Apparently pines and post oaks were sufficiently segregated that logging of pines produced little or no disturbance signal in the oak chronologies. This suggests that some caution is necessary when attempting to infer regional disturbance patterns from relatively few old trees (e.g. Nowacki and Abrams 1997).

The other old growth site, CL (Champion Longleaf), was also characterized in the presettlement forest by periods of growth increases interspersed with sharp growth declines. In contrast to the SAS post oak chronology, the growth increases at CL did not exceed the upper climate threshold and therefore cannot be attributed to disturbance. However, the growth declines did fall below the lower threshold attributable to climate. As at the TCF site discussed above, we suggest that periods of severe growth declines in presettlement longleafs at CL represent periods of frequent fire. Unlike the post oaks at SAS, it appears that fires did not kill longleaf pine trees at CL. Thus growth declines due to fires at this site were not accompanied by subsequent growth increases of a magnitude sufficient to indicate canopy disturbance. If our interpretation is correct, it suggests that frequent fires in presettlement longleaf stands were interrupted every 20-30 yrs by

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occasional fire free periods, perhaps sufficient to allow regeneration of longleaf and a few other trees. Based on data from a long-term experiment, Glitzenstein et al. (1995) suggested that brief intervals without fire might often be necessary for successful reproduction of longleaf pine.

The first evidence of elevated canopy disturbance at CL occurred around 1860. This may indicate the beginnings of minor cutting associated with increased settlement by people other than Native Americans. This minor initial disturbance was followed by "catastrophic" disturbance around 1890 (i.e. a GC pulse approaching 200 indicating almost complete canopy replacement). This disturbance may be associated with the first serious logging of the site. However, there are reasons why this is probably not the case. First, Wilson (1979) argued convincingly that substantial cutting in the northern tier of east Texas longleaf stands did not occur until the 1920's. This argument is supported by the GC chronologies of the other Texas longleaf sites (Longleaf Sites I and Eastern Longleaf Sites in Appendix A), all of which show major canopy opening events in the 1920's, but not before. In contrast, the CL longleaf chronology is the only one not to experience severe disturbance in the 1920's. The most likely explanation is that CL was subject to a major natural disturbance around 1890 and was consequently unfit for, or not worth the trouble of, logging 30 yrs later. Thus the stand was probably truly old-growth until very recently (i.e. shortly before our cores were collected), when Nature Conservancy supervised a "restoration" of the stand by removing the old hardwoods.

Following the major canopy opening event in 1890 the CL longleaf GC chronology indicates another period of growth declines at or below the threshold likely due to climate; again, we interpret this period, lasting until approximately 1930, as perhaps due to

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frequent fire. Subsequent to that date growth has largely fluctuated within the climatically-related limits, except for one minor disturbance in the late 1950's that may be related to recovery from drought. This entire period, i.e. from 1930 till the present, probably represents a period of prolonged fire exclusion, accounting for the depauperate condition of groundcover vegetation at the site.

*Regional GC Chronologies:* The regional GC chronology, including data from all 38 stands, is presented in Figure 9. This chronology strongly resembles the disturbance chronology constructed earlier (using similar, but not identical, methods) for Wier Woods, a mature pine-hardwood stand in Hardin County (Glitzenstein et al. 1986). The following features are common to both chronologies: (1) limited evidence for a period of elevated canopy disturbance between 1800-1810, (2) a relative hiatus in canopy disturbance lasting until approximately 1860 when settlement by non-native Americans began in earnest, (3) a disturbance peak around 1900 possibly associated with the great Galveston Hurricane which produced widespread forest disturbance in parts of east Texas (Bray 1901) (4) a period of severe canopy disruption lasting from approximately 1910 - 1933; this undoubtedly represents the main period of logging of old growth forests in east Texas, (5) a period of elevated disturbance during the mid 1950's and early 1960's. Unlike the 1910-1930 period, most disturbances during this latter period were of low severity; possible explanations include (a) drought related mortality due to the severe 1950's drought, and (b) Hurricane Carla in 1961. It is also possible that recovery from drought, independent of disturbance, contributed to the GC peak during this period.

Finally, the regional GC chronology indicates a recent increase in disturbance during

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the mid 1980', perhaps due to continuing beetle outbreaks as well as drought-related disturbance in the early 1980's.

To check for geographical patterns in disturbance, the release chronology was plotted separately for (a) southern ( $< 30.5$  degrees latitude) and northern ( $> 30.5$  degrees latitude) sections (Figure 10), and (b) eastern (longitude  $< 94.5$  degrees) and western (longitude  $> 94.5$ ) sections (Figure 11). The main differences were (a) the lack of a 1900 release peak in the north, suggesting that impacts of the Galveston Hurricane were limited to southern forests nearer to the Gulf of Mexico, and (b) a much more pronounced 1950's release peak in the western section, suggesting greater direct and/or indirect drought effects in this drier part of the study area.

In addition to analyzing releases, as described above, we also analyzed suppressions. There were, in fact, two particularly prominent periods of suppression (Figure 9, top). The first, in 1946, was clearly interpretable as the beginning of a decline associated with the 1950's drought. The second, in 1977, was also associated with drought, in this case the drought of the early 1980's. The latter peak is interesting because, though 1980 is a known drought year, drought during the 1970's and 1980's was much less severe than during the 1950's (Figure 12). The fact that the two suppression peaks were clearly associated with droughts rather than disturbances suggests that the Nowacki and Abrams (1997) method is not adequate for filtering out effects of unusually severe or prolonged droughts, i.e. the relationship between climate and the GC chronology is obviously non-linear for high levels of drought.

In further analyzing the suppression peaks described above, another interesting pattern was uncovered. This is that responses of pine and hardwood species during

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these stressful years differed significantly. Mean percent growth change in 1946 was  $-28.9 \pm 7.43$  (95% confidence interval) for pines (i.e. an average decline in growth of approximately 29% compared to the prior decade), but only  $-0.61 \pm 7.53$  for hardwoods. This appears to show that the 1950's drought had a severe negative impact on pines but hardly any effect on hardwoods. This conclusion is somewhat misleading however; if only upland hardwoods are included (i.e. bottomland oaks *Quercus phellos*, *Q. lyrata*, *Q. michauxii* and *Q. laurifolia* are excluded) the mean GC for hardwoods in 1946 is  $-4.08 \pm 6.3$ , evidence for at least a moderate growth decline. Nevertheless it seems quite clear that detrimental effects of the 1950's drought were much greater for pines than for hardwoods (i.e. oaks and beech, the hardwood species included in this study).

Growth declines beginning in 1977 followed a much different pattern. Compared to the 1946 - 1955 period, pine declines were somewhat less severe (i.e. mean GC =  $-20.52 \pm 4.29$ ), but hardwood declines were much more severe (mean GC =  $-14.55 \pm 4.59$ ). Thus stress experienced by hardwoods and pines was more equivalent in 1977 - 1986 than in 1946 - 1955. One hypothesis to explain these patterns involves the prior history of disturbance and stand development in east Texas forests. As we have shown, most stands were subject to major disturbance during 1910 - 1933 and therefore consisted of mostly young trees at the time of the 1950's drought. At this time, canopy stratification would have been extreme, with fast growing pines overtopping smaller, suppressed hardwoods (see Glitzenstein et al. 1986). Furthermore, the young pines were likely located in large canopy openings and growth was close to maximum. Under these conditions, where competition was relatively unimportant, severe drought would be expected to substantially reduce growth. In contrast, the hardwoods, already suppressed by pine

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competition, may have been less likely to show drought-related growth effects, though effects on mortality may have been considerable. Thirty years later, at the time of the early 1980's drought, pines and hardwoods were likely in more equivalent canopy positions in most stands, and may therefore have shown more similar responses to stressful climate.

Given that droughtiness, as measured by the PDSI, tends to increase from east to west, it might be expected that growth declines during droughts might also increase with longitude. To test this hypothesis, we examined the correlation between percent GC and longitude for pines and hardwoods during each of the two main drought periods. Results of these correlations were consistent with the differences already discussed. Percent GC was significantly negatively correlated with longitude for pines in 1946 ( $r = -0.32$ ,  $P = 0.06$ ,  $n = 34$ ) but not in 1977 ( $r = 0.26$ ,  $P = 0.13$ ) whereas for hardwoods the opposite result was obtained (i.e. in 1946, GC vs longitude  $r = -0.17$ ,  $P = .18$ ,  $n = 65$ ; in 1977  $r = -0.28$ ,  $P = 0.02$ ). Thus, for both groups, longitudinal effects on growth were more pronounced during periods when overall growth declines were more severe.

*Other Climate Analyses:* The above results demonstrate that prolonged severe droughts do influence growth change chronologies, even to the point of confounding or confusing inferences about disturbance history. This raises the question of whether growth change values and PDSI differences are in general strongly related. The answer to this question is clearly "no". This is shown first of all by the fact that, for most species, the large majority of growth change chronologies were not significantly correlated with PDSI difference chronologies (Table 1). To some extent, loblolly pine was an exception to this

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generalization: 11 of 19 (57.9 %) chronologies of this species were significantly positively correlated with PDSI differences (Table 1). However, even in this case the mean correlation was only 0.22 indicating at best a weak relationship between growth and climate.

Most of the other upland (i.e. mesic or dry site) species also had some meaningful proportion (i.e. > 20%) of chronologies where growth was significantly and positively related to climate. In contrast, there were almost no positive significant correlations for bottomland species, though in several such cases there were significantly negative correlations (Table 1). This suggests that prolonged wet periods may result in depressed growth of bottomland oaks. There were also a few significant negative correlations for dry site species, e.g. shortleaf pine and blackjack oak (Table 1). One possible explanation for this latter result is that wet periods may lead to greater fuel accumulations, and hence hotter and more destructive fires, resulting in growth suppressions. The fact that such negative effects were observed only rarely in dry site species suggests that these effects are typically less important than positive effects of increased precipitation on such sites.

Despite some few significant correlations, as discussed above, growth change chronologies in our study were generally uncorrelated with PDSI differences. Similar results were obtained by Nowacki and Abrams (1997), who interpreted this to mean that climate was a relatively unimportant influence on growth as compared to disturbance and competition. We agree with this interpretation, though it should be noted that once these factors are statistically accounted for, climate does account for relatively substantial percentages of the residual variation (see results and discussion of ARSTAN chronologies above).

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**PCA results:** The first 5 eigenvalues of the GC RPCA accounted for a rather extraordinary 86% of the overall variation. The first axis, which accounted for 21.8% of the variation, was significantly influenced by differences among species and sites, not quite significantly related to community type, and not at all related to geography (Table 2). As in the ARSTAN PCA, the species loadings across this first axis revealed an important phylogenetic effect, i.e. pines and hardwoods were clearly separated (Figure 13). The implication is that these two species groups respond as differently to decade-scale trends in climate and disturbance as they do to short-term climatic variation.

Results of the ARSTAN analyses described above revealed phylogenetically based differences within hardwood species, as well as between hardwoods and pines. However, no such within hardwood differences were apparent in the GC RPCA. Instead, the sorting of hardwoods in this analysis (i.e. oaks and beech) was more related to ecological differences. In general, species typical of driest sites (*Quercus marilandica*, *Q. falcata*, *Q. stellata*) had the highest first axis loadings, species typical of mesic sites (*Q. alba*, *Q. nigra*, *F. grandifolia*) had somewhat lower first axis loadings, and species typical of wet sites (*Q. michauxii*, *Q. phellos*) had the lowest loadings along this axis (though even these species loaded more highly than the pines)(Figure 12). The major exception to this generalization was *Quercus lyrata* (overcup oak) which loaded along with the three dry site species rather than as a bottomland species. This result may be due in part to low sample size (only 2 chronologies for this species) and also to the fact that one of the two chronologies (i.e. Navosota floodplain) was obtained from a population located precisely on the western range limit for this species where conditions may be more xeric than the species might ordinarily encounter.

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The second axis of the GC RPCA, which accounted for about 19% of the variation, was significantly related to geography (combined effects of latitude and longitude), but none of the other factors, including species (Table 2). This axis may reflect climate (i.e. drought) and disturbance (i.e. 1900's and other hurricanes) gradients discussed in previous sections.

Axis 3 of the GC RPCA, which explained 16.8% of the variance, was significantly related to site and habitat influences (Table 2). The higher correlation was with site, suggesting that the habitat effect was primarily a reflection of the site effect (i.e. species living on the same site had similar disturbance histories), and that habitat had little additional explanatory power.

Axis 4 explained 9.4% of the variance. Like axis 1, loadings on this axis were significantly correlated with species and site. Also, like axis 1, pines and hardwood loadings were clearly separated along axis 4. Thus a 2-dimensional plot of axis 1 and axis 4 loadings provided the cleanest visual display of the "phylogenetic" effect in the GC RPCA (Figure 12). Unlike axis 1, loadings of hardwood species along axis 4 were not easily interpreted.

Finally, axis 5 (6.4% of the variation) was strongly correlated with site but none of the other explanatory variables. Overall, site was correlated with 4 of the 5 RPCA axes (all except axis 2); thus we might say that site effects were at least related to approximately 55% of the overall variance in GC chronologies. Species differences were statistically related to two of the axes, for a total of 31.2% of the variance. Habitat and geography were significantly correlated with one axis apiece and cumulative effects of these factors were appeared to be less important than species and site effects. The fact that site was

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correlated to multiple RPCA axes may indicate groups of sites, each responding to a different set of disturbances.

One problem with the dataset used in this study is that effects of habitat were not controlled for in the experimental design, and species and site effects were confounded (i.e. not all species were present at all sites). Given these problems it is difficult to precisely partition variance cleanly among explanatory factors, and the above analysis must be regarded as very preliminary. Nevertheless, as with the ARSTAN approach utilized in the first section, the GC analyses described herein may provide a new and more quantitative approach to the study of disturbance effects in forest dynamics.

## NON-TECHNICAL SUMMARY

A ring width series obtained from an increment core of a given tree is referred to as a tree ring chronology and a collection of chronologies from a given species and stand is referred to as a stand chronology. Untransformed chronologies are difficult to work with due to a number of statistical problems, including long-term trends in the data and large differences in growth among trees. In this study we used two different transformations of the raw ring width data to study different components of overall tree growth. The first transformation, which focuses on year to year variability, is referred to as ARSTAN (autoregressive standardized). This transformation is useful for studying effects of short term influences on tree-growth, particularly annual variation in climate. The second transformation is PGC (percent growth change) which compares growth of subsequent and preceding ten-yr periods. PGC tends to filter out short term effects, allowing the detection

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of medium scale effects due to disturbance and prolonged climatic events (i.e. droughts which last several years).

These transformations were applied to 99 chronologies obtained from 38 stands distributed from western Louisiana to central Texas. Important results of the study included the following: (1) The most interesting result of the ARSTAN analyses was the detection of a so-called "phylogenetic" effect, i.e. the tendency for evolutionarily related groups of species to behave similarly in terms of patterns of short-term variation in tree-ring growth. Correlations between ARSTAN generated tree-ring indices and climate data revealed that the phylogenetic effect was indeed due to differences among species groups in how the groups responded to climatic variation, particularly month and year of precipitation. The clearest distinction was between pines and hardwoods, but there were also important differences even within genera (i.e. white and black oaks subgenera showed different climate response patterns). The implication of these results is that changes in seasonality and not just magnitude of precipitation may have important effects on competition and species composition of forests. (2) In addition to the phylogenetic effect, another important result of the ARSTAN analyses was the finding of clear geographical trends in how climate influences tree growth. Most interesting was the finding that white and black oak responses to climate appear to converge as one moves from east to west, i.e. from an area of favorable climate to a more stressful situation close to the edge of the range of many species. (3) GC analyses indicated that, even for apparently mature stands, disturbance history of the West Gulf region was dominated by widespread intensive logging early in the present century. However, there were indications of geographical gradients in natural disturbance, with respect to both hurricanes and major

drought events. Severe and prolonged droughts, such as occurred in the 1950's and 1980's, resulted in sharp growth declines ( $> 25\%$  as compared to the prior decade) and increases in canopy disturbance which became more pronounced towards the western edge of the study area. Another interesting result was that hardwood and pine species appeared to respond differently during two major drought periods; i.e. pine growth declined to a much greater extent than did hardwood growth during the mid 1950's drought, whereas the opposite situation prevailed during the 1980's. Consistent with this result, multivariate analyses of PGC chronologies revealed a phylogenetic effect similar to that obtained with ARSTAN. This suggests that pines and hardwoods respond very differently to climate and disturbance at a variety of temporal scales.

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Table 1. Summary of results of climate correlations (i.e. percent growth change vs. summer PDSI difference). Species are ranked first of all on the basis of percentage of chronologies with positive, significant correlations and, secondarily (i.e. in case of ties) based on percentages of negative, significant correlations. Except for the first column, numbers are percentages. Numbers in the "species column" are sample sizes (i.e. number of chronologies for that species).

| SPECIES                        | SIGNIFICANT<br>AND POSITIVE | SIGNIFICANT<br>AND NEGATIVE | NON-<br>SIGNIFICANT |
|--------------------------------|-----------------------------|-----------------------------|---------------------|
| <i>Quercus incana</i> (1)      | 100.0                       | 0.0                         | 0.0                 |
| <i>Pinus taeda</i> (19)        | 57.9                        | 8.3                         | 33.8                |
| <i>Fagus grandifolia</i> (9)   | 44.4                        | 0.0                         | 55.6                |
| <i>Quercus alba</i> (11)       | 27.3                        | 9.1                         | 63.6                |
| <i>Quercus stellata</i> (4)    | 25.0                        | 0.0                         | 75.0                |
| <i>Pinus palustris</i> (9)     | 22.2                        | 0.0                         | 77.8                |
| <i>Quercus falcata</i> (10)    | 20.0                        | 8.3                         | 70.0                |
| <i>Quercus laurifolia</i> (1)  | 0.0                         | 100.0                       | 0.0                 |
| <i>Quercus marilandica</i> (1) | 0.0                         | 66.7                        | 33.3                |
| <i>Quercus lyrata</i> (2)      | 0.0                         | 50.0                        | 50.0                |
| <i>Pinus echinata</i> (6)      | 0.0                         | 33.3                        | 66.7                |
| <i>Quercus phellos</i> (3)     | 0.0                         | 33.3                        | 66.7                |
| <i>Quercus nigra</i> (16)      | 0.0                         | 12.5                        | 87.5                |
| <i>Quercus michauxii</i> (5)   | 0.0                         | 0.0                         | 100.0               |

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Table 2. ANOVA (1-way) and regression (for lat+lon effect) analysis results of factor loadings from RPCA of GC chronologies.

| AXIS 1                      |           |           |          |          |
|-----------------------------|-----------|-----------|----------|----------|
| <u>INDEPENDENT VARIABLE</u> | <u>DF</u> | <u>SS</u> | <u>F</u> | <u>P</u> |
| SPECIES                     | 11,71     | 3.41      | 2.48     | 0.01     |
| SITE                        | 21,48     | 5.08      | 2.40     | 0.01     |
| COMMUNITY                   | 5,78      | 1.32      | 1.85     | 0.11     |
| LATITUDE+LONGITUDE          | 2,82      | 0.40      | 1.38     | 0.26     |

| AXIS 2                      |           |           |          |          |
|-----------------------------|-----------|-----------|----------|----------|
| <u>INDEPENDENT VARIABLE</u> | <u>DF</u> | <u>SS</u> | <u>F</u> | <u>P</u> |
| SPECIES                     | 11,71     | 1.99      | 1.50     | 0.15     |
| SITE                        | 21,48     | 2.68      | 1.03     | 0.45     |
| COMMUNITY                   | 5,78      | 0.77      | 1.18     | 0.33     |
| LATITUDE+LONGITUDE          | 2,82      | 0.88      | 3.87     | 0.03     |

| AXIS 3                      |           |           |          |          |
|-----------------------------|-----------|-----------|----------|----------|
| <u>INDEPENDENT VARIABLE</u> | <u>DF</u> | <u>SS</u> | <u>F</u> | <u>P</u> |
| SPECIES                     | 11,71     | 2.93      | 1.43     | 0.18     |
| SITE                        | 21,48     | 7.59      | 2.35     | 0.01     |
| COMMUNITY                   | 5,78      | 2.16      | 2.39     | 0.05     |
| LATITUDE+LONGITUDE          | 2,82      | 0.22      | 0.56     | 0.58     |

| AXIS 4                      |           |           |          |          |
|-----------------------------|-----------|-----------|----------|----------|
| <u>INDEPENDENT VARIABLE</u> | <u>DF</u> | <u>SS</u> | <u>F</u> | <u>P</u> |
| SPECIES                     | 11,71     | 3.18      | 4.11     | 0.00     |
| SITE                        | 21,48     | 3.13      | 1.82     | 0.04     |
| COMMUNITY                   | 5,78      | 0.53      | 1.07     | 0.39     |
| LATITUDE+LONGITUDE          | 2,82      | 0.08      | 0.41     | 0.67     |

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| AXIS 5                      |           |           |          |          |
|-----------------------------|-----------|-----------|----------|----------|
| <u>INDEPENDENT VARIABLE</u> | <u>DF</u> | <u>SS</u> | <u>F</u> | <u>P</u> |
| SPECIES                     | 11,71     | 0.86      | 1.20     | 0.30     |
| SITE                        | 21.48     | 3.03      | 2.40     | 0.01     |
| COMMUNITY                   | 9,78      | 0.43      | 1.13     | 0.35     |
| LATITUDE+LONGITUDE          | 2,82      | 0.01      | 0.10     | 0.89     |

## FIGURE LEGENDS

1. Locations of tree-ring sample sites in Louisiana and Texas.
2. Surface plots of winter and summer average precipitation and maximum temperature over the Big Thicket region. The x-axis is longitude, the y-axis is latitude and the Z axis is climate in either centimeters of precipitation or degrees Celsius.
3. Factor 1-2 loadings of ARSTAN RPCA plotted according to species (bottom) and site (top). Species codes are as follows: FAGR (*Fagus grandifolia*; beech), PIEC (*Pinus echinata*; shortleaf pine), PIPA (*Pinus palustris*; longleaf pine), PITA (*Pinus taeda*; loblolly pine), QUAL (*Quercus alba*; white oak), QULY (*Quercus lyrata*; overcup oak), QUMA (*Quercus marilandica*; blackjack oak), QUMI (*Quercus michauxii*; basket oak), QUNI (*Quercus nigra*; water oak), QUPH (*Quercus phellos*; willow oak), QUST (*Quercus stellata*; post oak).
4. Factor 3-4 loadings of ARSTAN RPCA plotted according to species (bottom) and site (top). See legend of Figure 3 for species codes.
5. Box plots of the four varimax rotated principal components based on 99 tree-ring chronologies. Based on results of Figs. 3-4 the loadings have been classified into four phylogenetic groups: American beech (FAGR), the white oak subgenus (QUWO), the black oak subgenus (QUBO), and the pine species (PISP). In addition, the loadings have been split into east and west regions along the 94.5 degree W meridian.
6. Climate correlation function plots for the tree-ring chronologies from the western region only. The monthly correlations were computed over a 17-month dendroclimatic year beginning in May of the previous growing season and ending in September of the current growth year. The plots have been organized by phylogenetic group to illustrate the high degree of similarity in climate response within each group. All show pronounced sensitivity to drought.
7. Climate correlation function plots for the tree-ring chronologies from the eastern region only.

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See the Fig. 6 caption for details.

8. Factor analysis of the climate correlation functions shown in Figs. 8 and 9. Three significant factors were identified using the Rule-N test. The factor loadings are plotted as box plots as in Fig.

4. The plots in the right column are the factor scores associated with the loadings. The scores show the pattern of monthly precipitation and temperature associated with each factor. These climate correlation factors show the same basic phylogenetic separations as the tree-ring chronologies themselves, indicating that differing responses to climate are the driving force behind the patterns in the tree-ring data.

9. Regional GC chronology based on analyses of 85 chronologies encompassing the period 1930-1983. The bottom graph includes data on frequency of releases (i.e. pulses in growth exceeding the amount predicted by climate or the 25% default cutoff) and the top graph is the frequency of suppressions (i.e. equivalent to releases, but for the lower climate threshold instead of the upper one). Each release or suppression is tabulated according to the "peak" year (i.e. the single highest or lowest year in a series of years exceeding or falling beneath the climate thresholds).

10. Release chronologies for southern and northern sections of the study area. See also legend to figure 9.

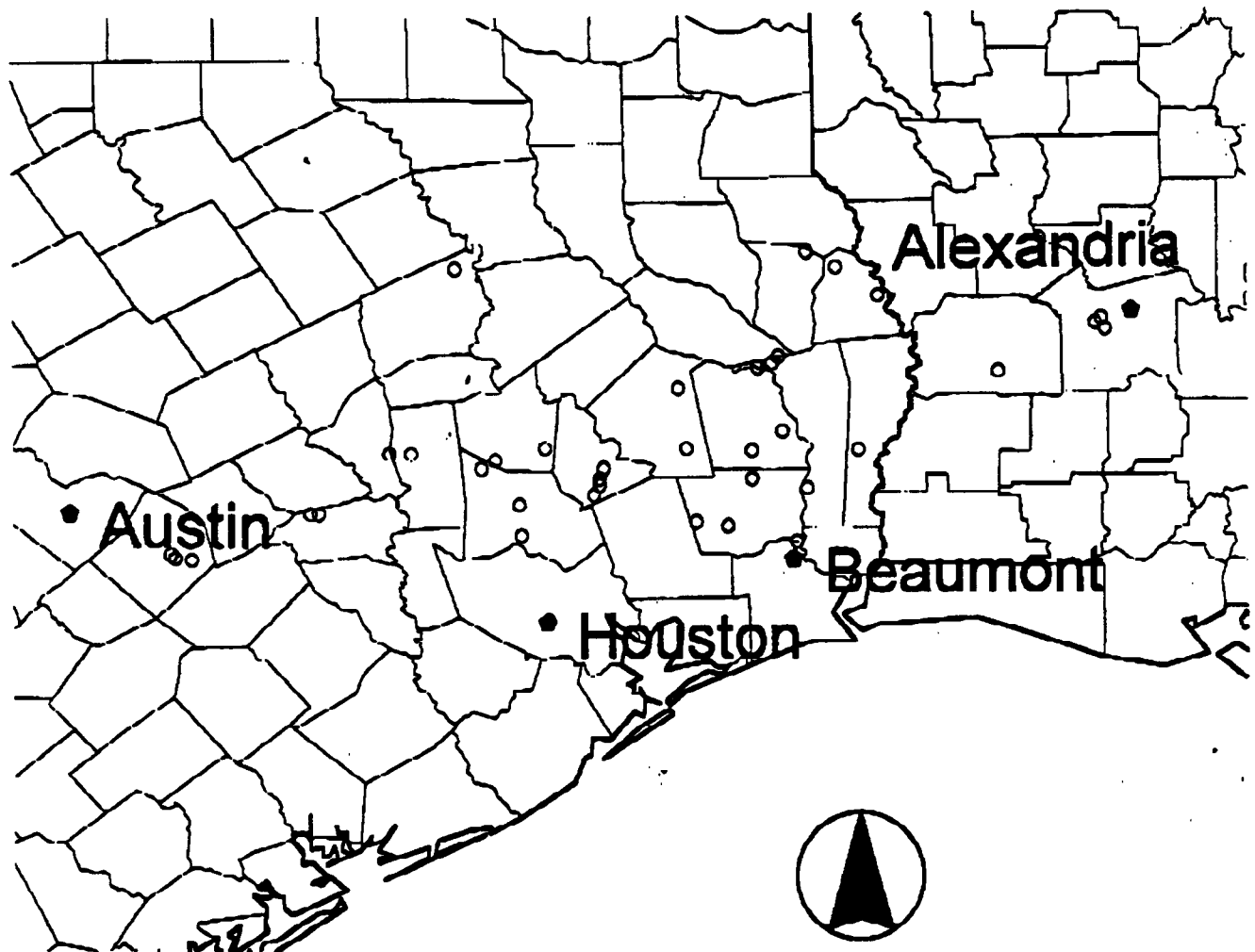
11. Release chronologies for eastern and western sections of the study area. See also legend to figure 9.

12. PDSI difference curves for different parts of the study area. Curves are displayed from the driest (i.e. most westerly) to the most moderate (i.e. easterly) ends of the climate gradient.

13. Mean GC RPCA factor loadings for species included in this study. The two axes shown are the ones for which species was significantly related to the factor. Codes are the same as shown in the legend to Figure 3.

FIGURE 1

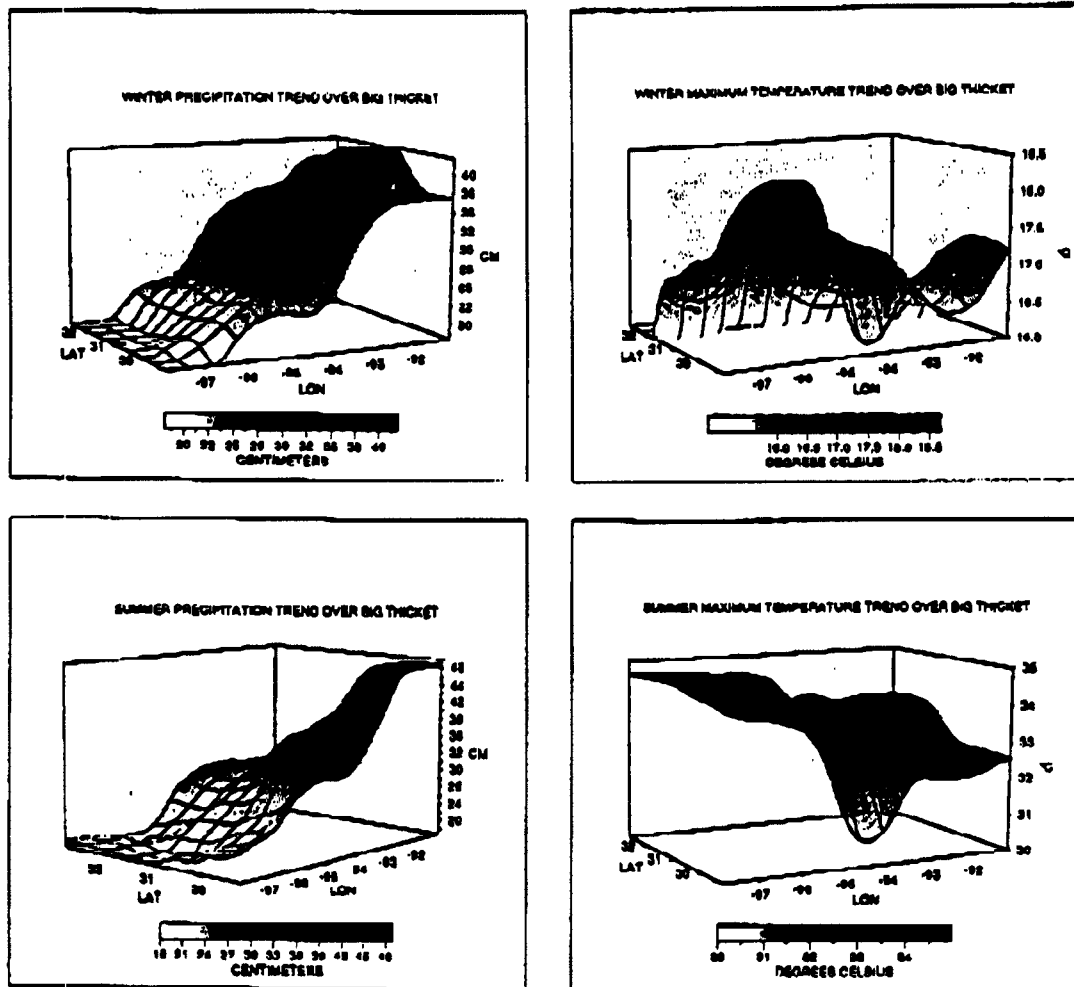
# TREE RING SITES



100 0 100 200 Kilometers

A horizontal scale bar with alternating black and white segments, corresponding to the 100, 0, 100, and 200 kilometer markings.

FIGURE 2







## BIG THICKET REGION TREE-RING CHRONOLOGIES

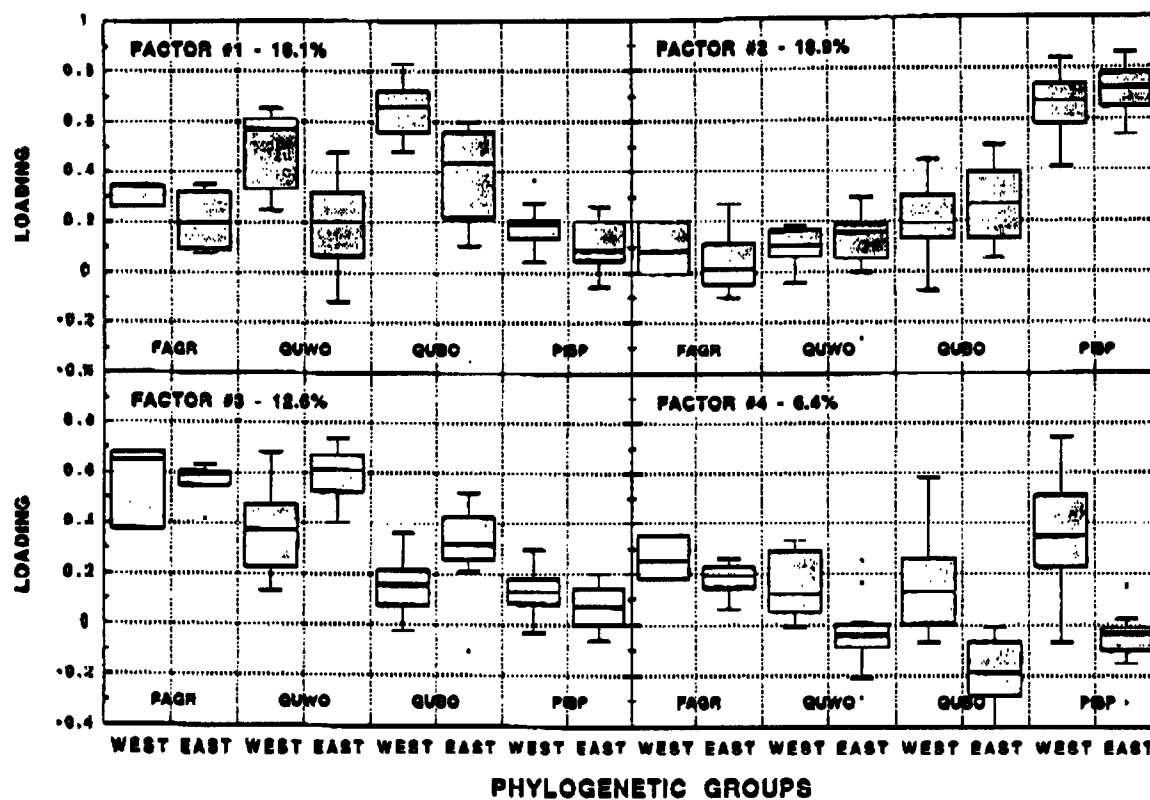


FIGURE 6

## WESTERN TREE-RING CHRONOLOGIES

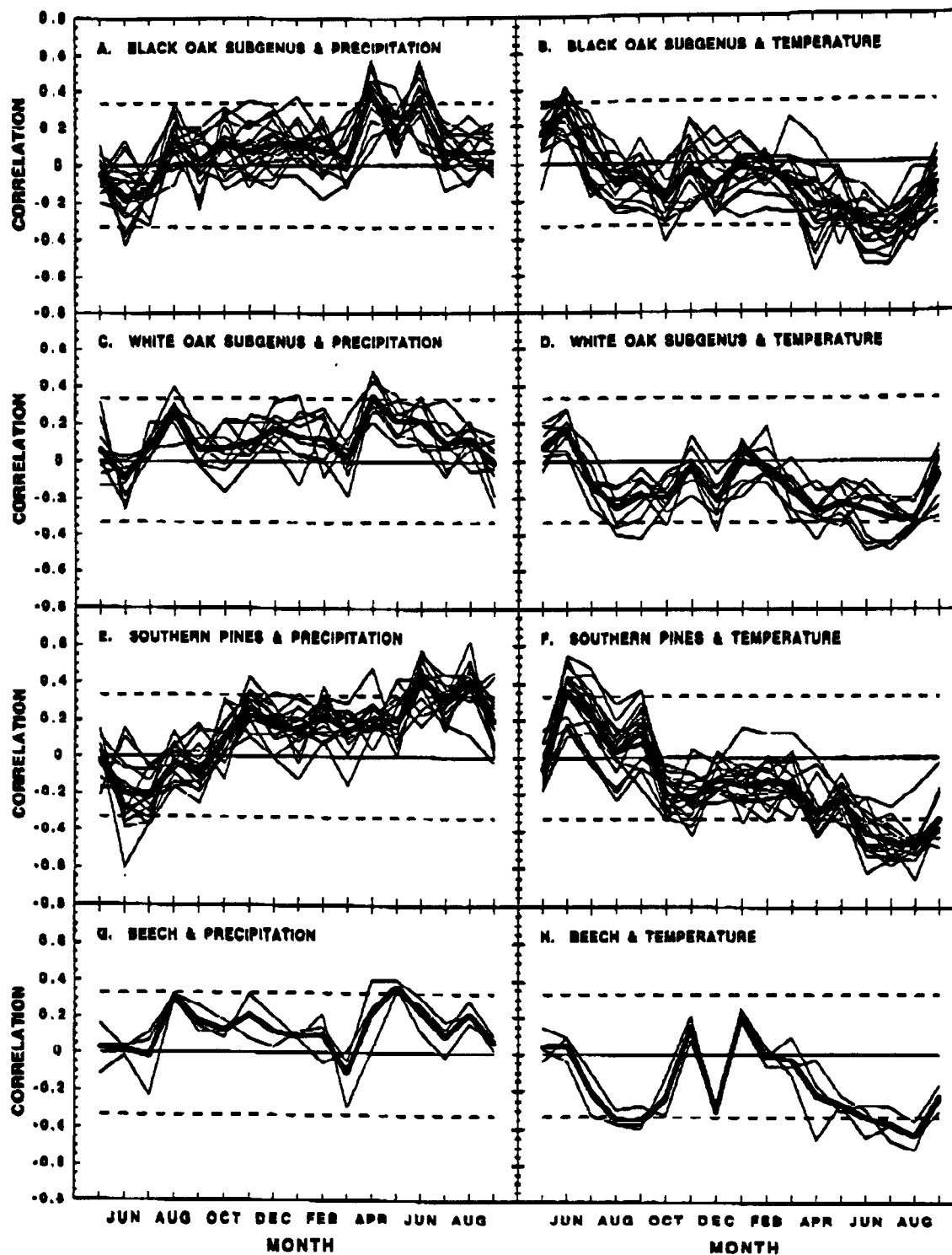


FIGURE 7

## EASTERN TREE-RING CHRONOLOGIES

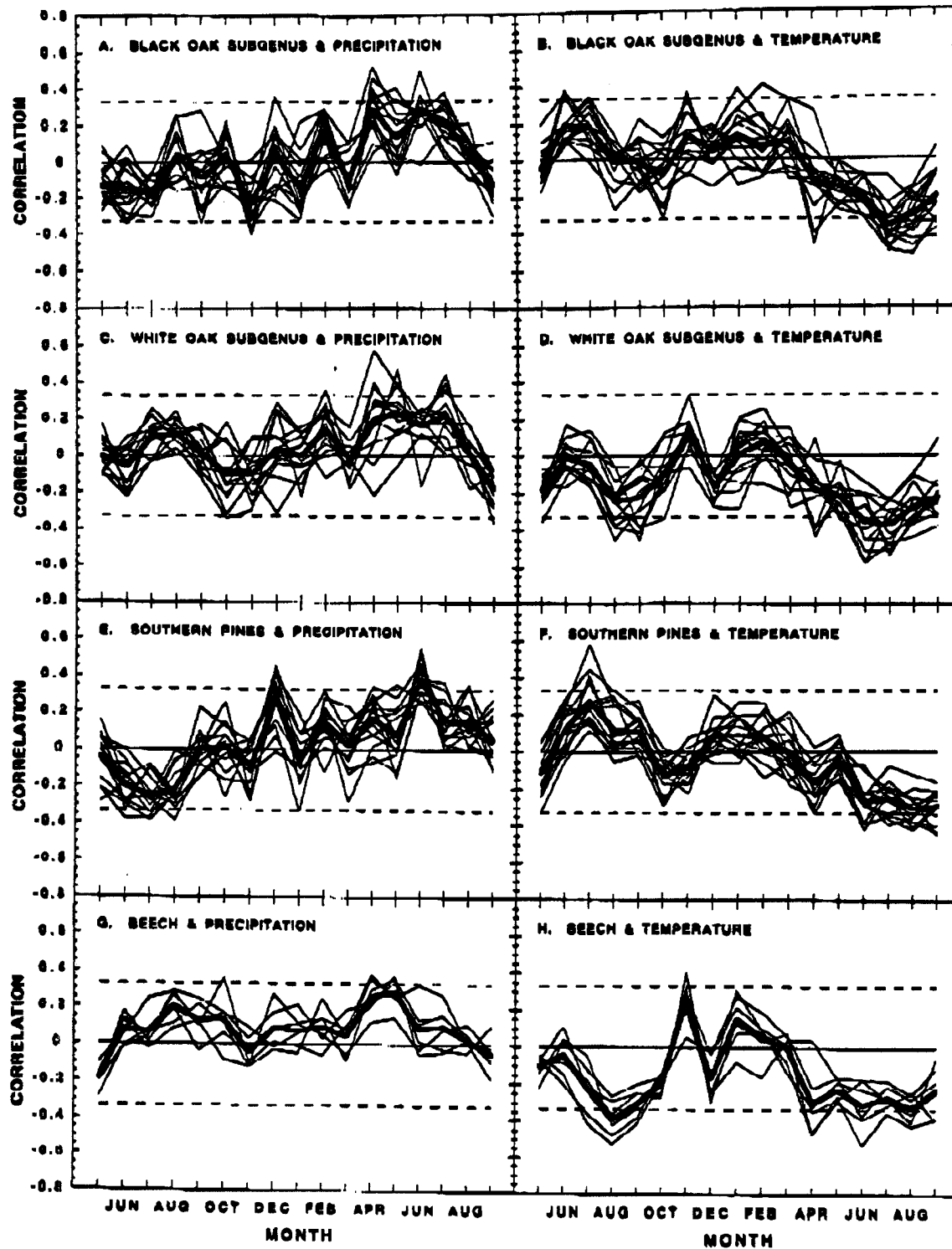


FIGURE 8

## CLIMATE FACTOR ANALYSIS

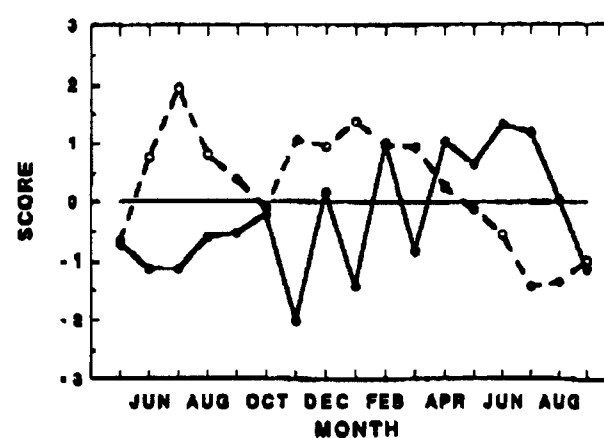
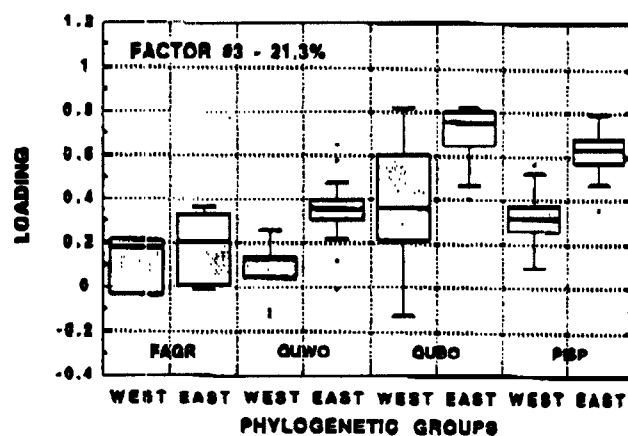
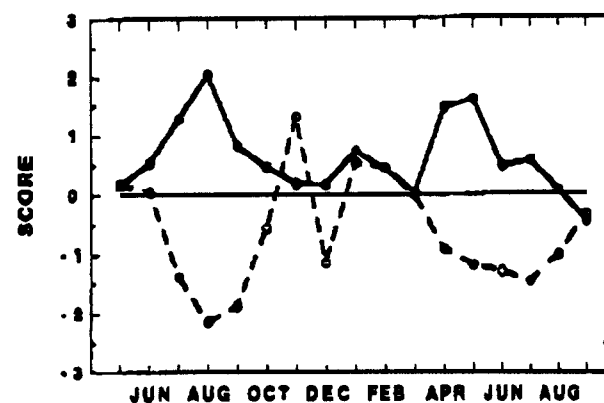
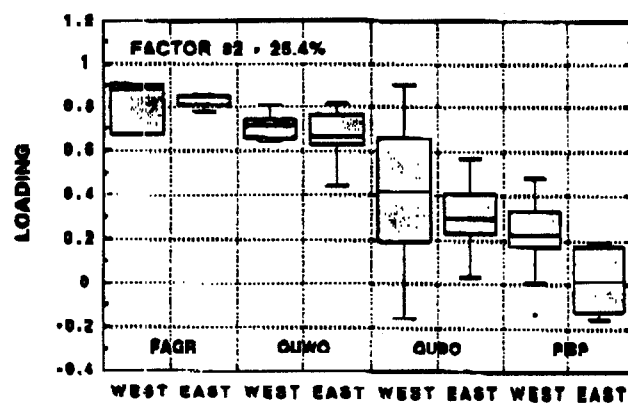
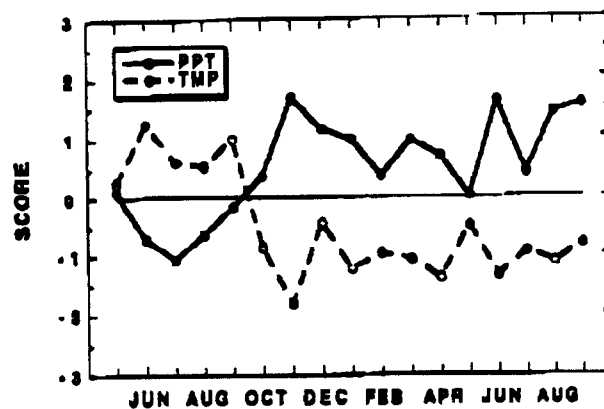
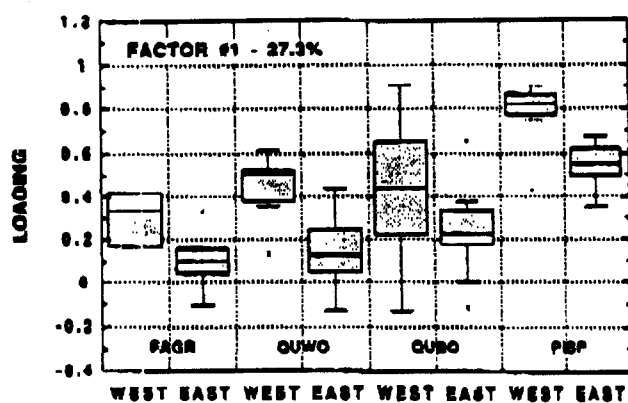
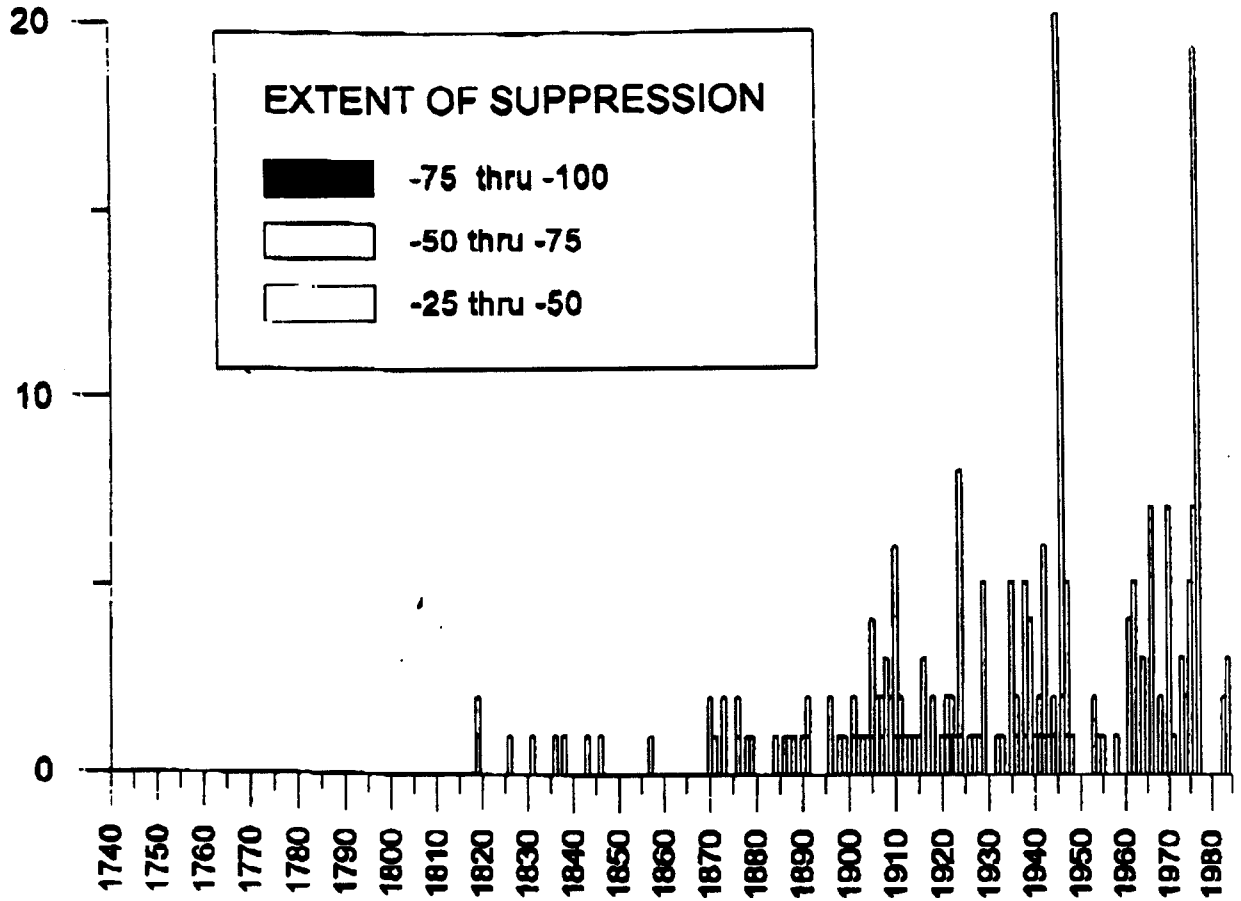


FIGURE 9

FREQUENCY OF SUPPRESSION PEAKS



FREQUENCY OF RELEASE PEAKS

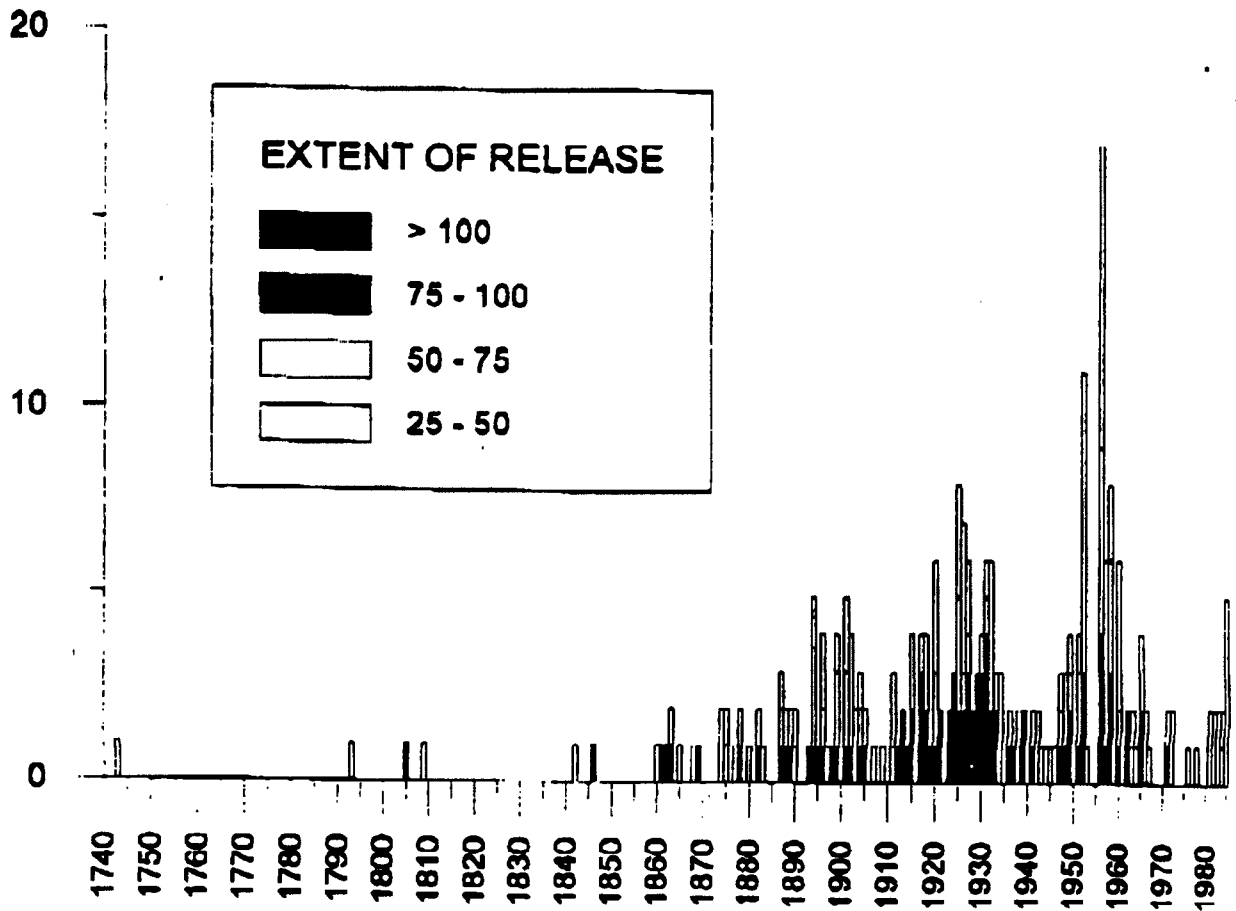
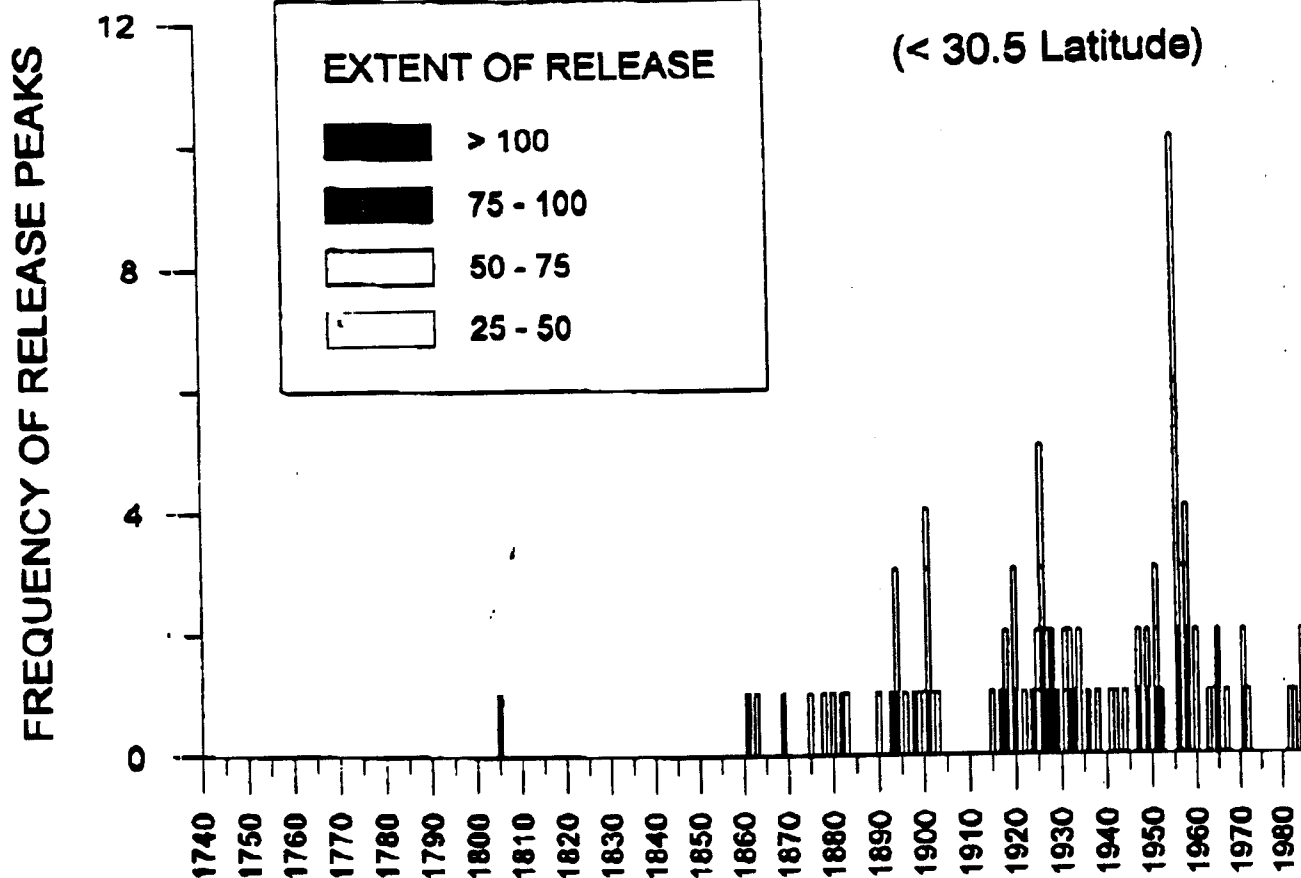


FIGURE 10

# SOUTHERN SECTION

(< 30.5 Latitude)



**FREQUENCY OF RELEASE PEAKS**

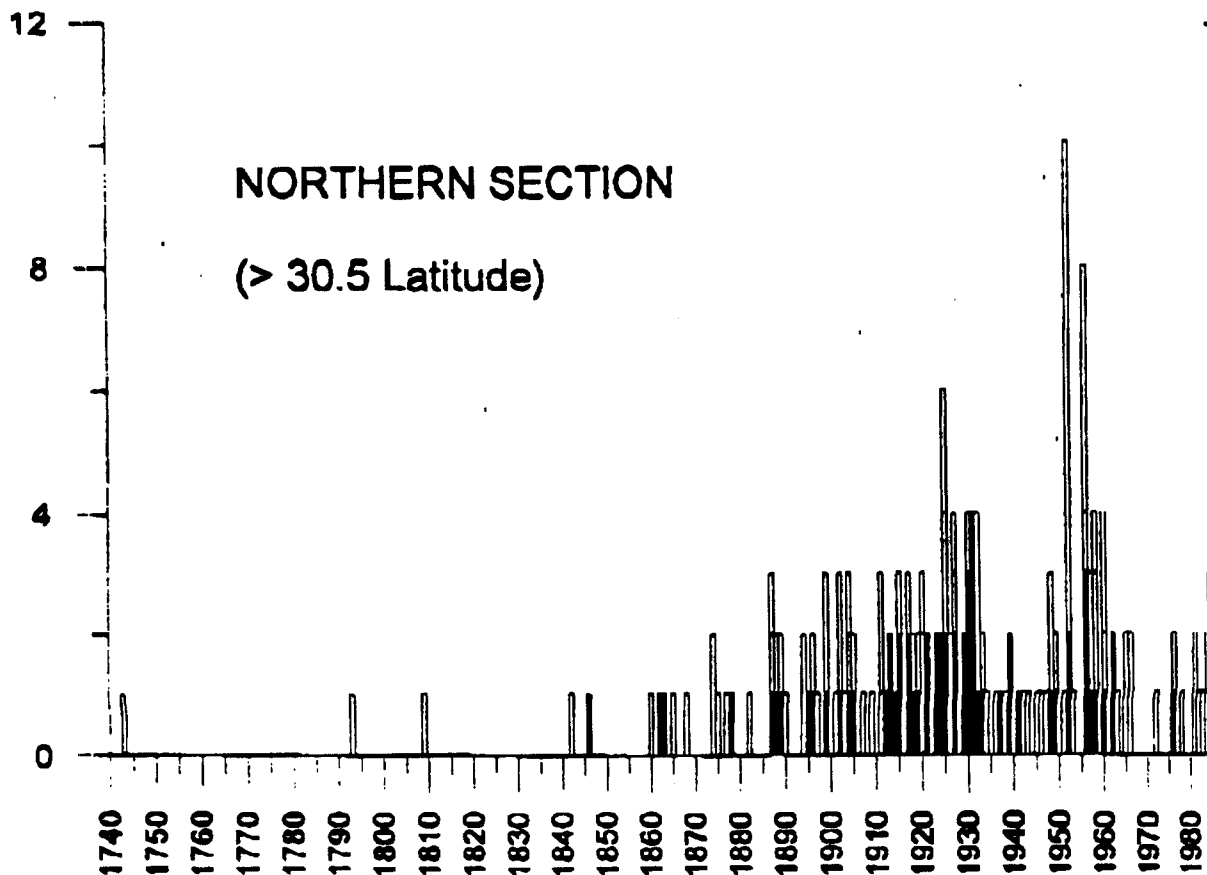
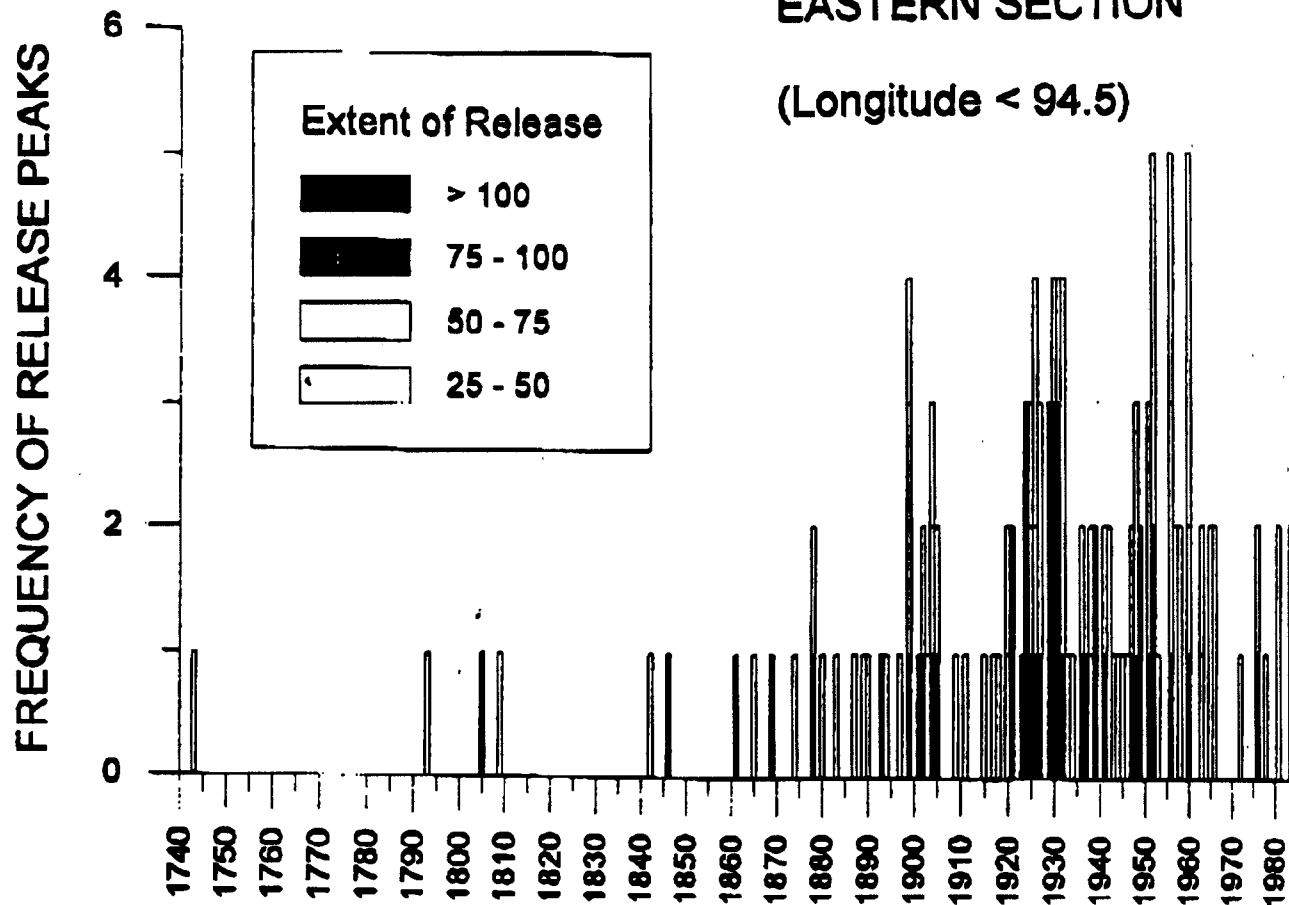


FIGURE 11

## EASTERN SECTION

(Longitude &lt; 94.5)



## FREQUENCY OF RELEASE PEAKS

## WESTERN SECTION

(Longitude &gt; 94.5)

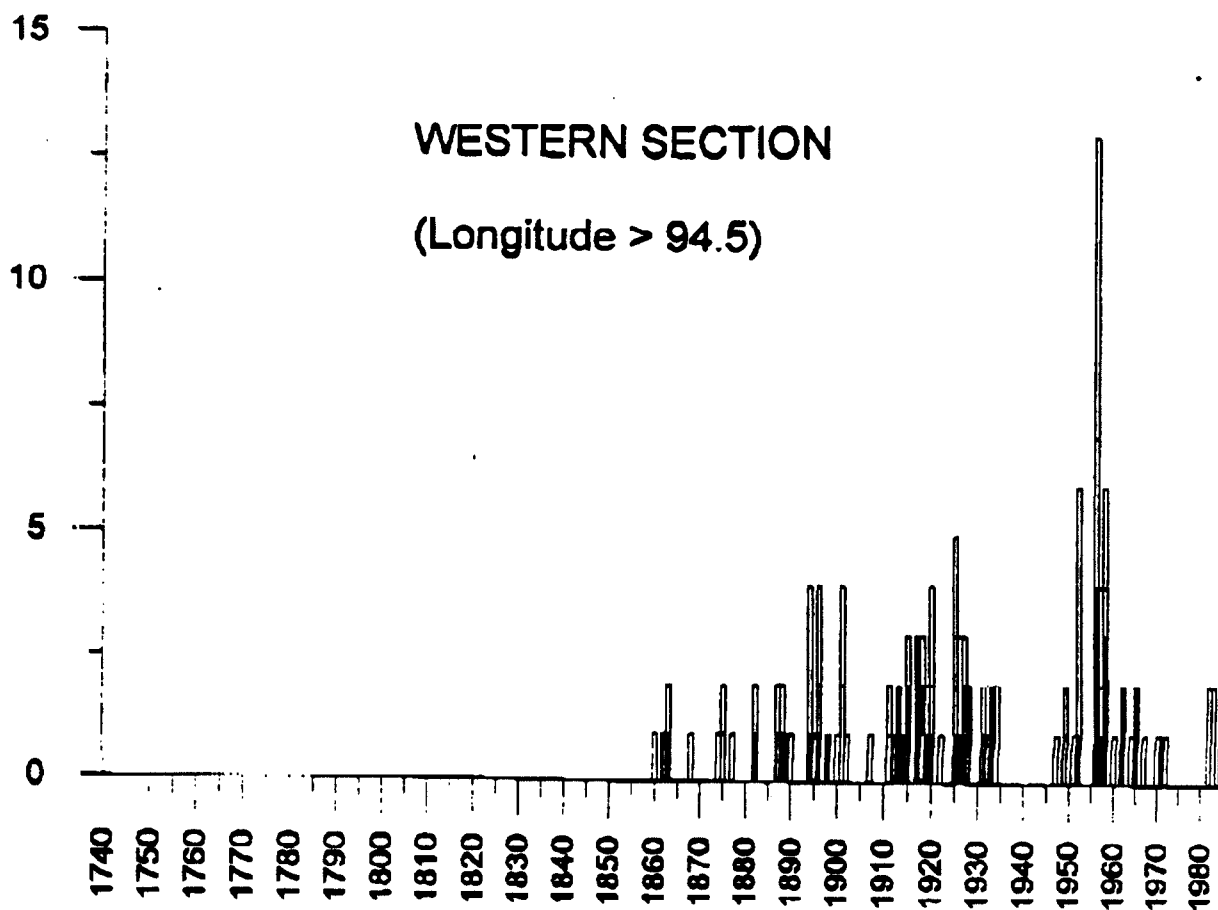


FIGURE 12

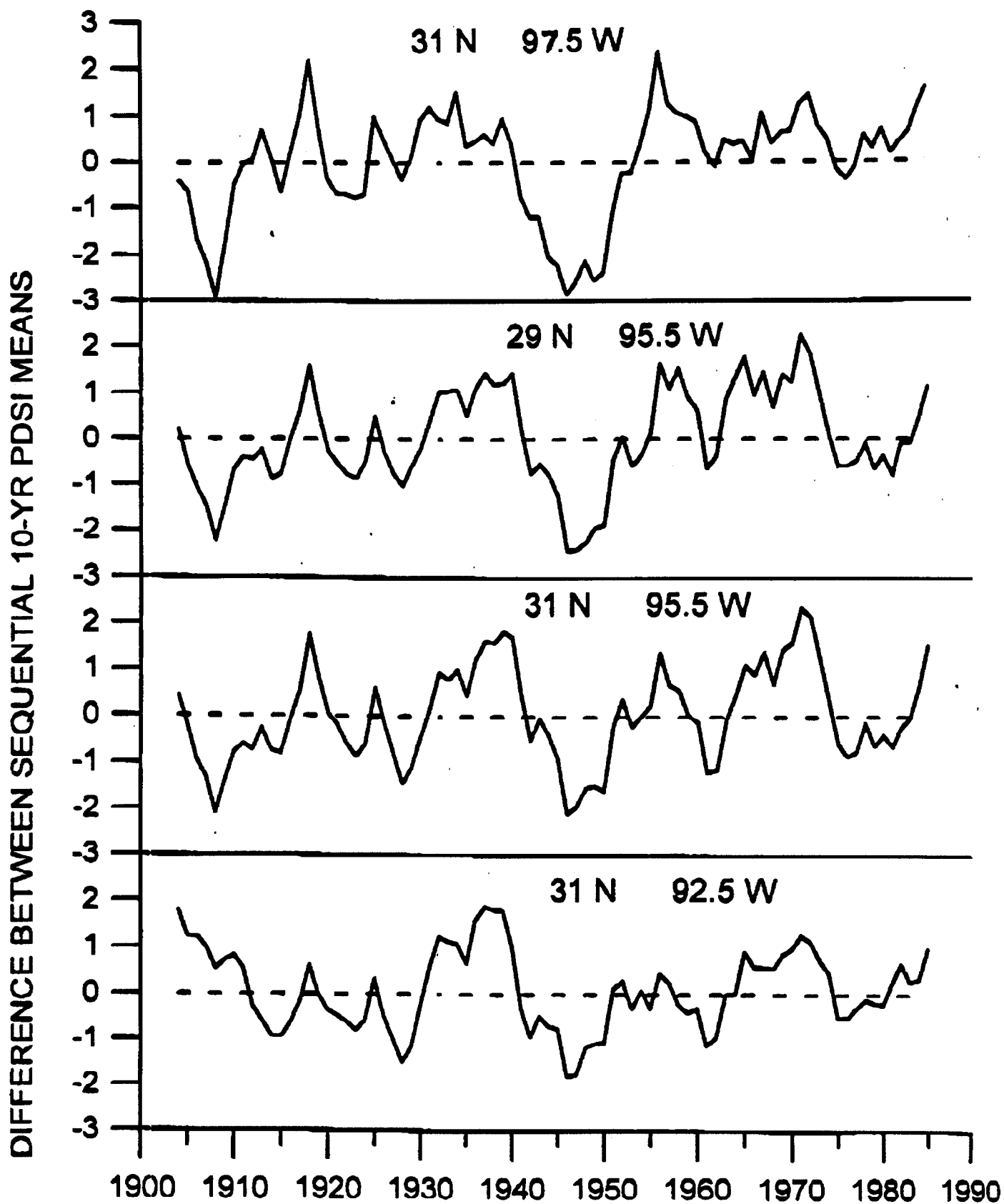
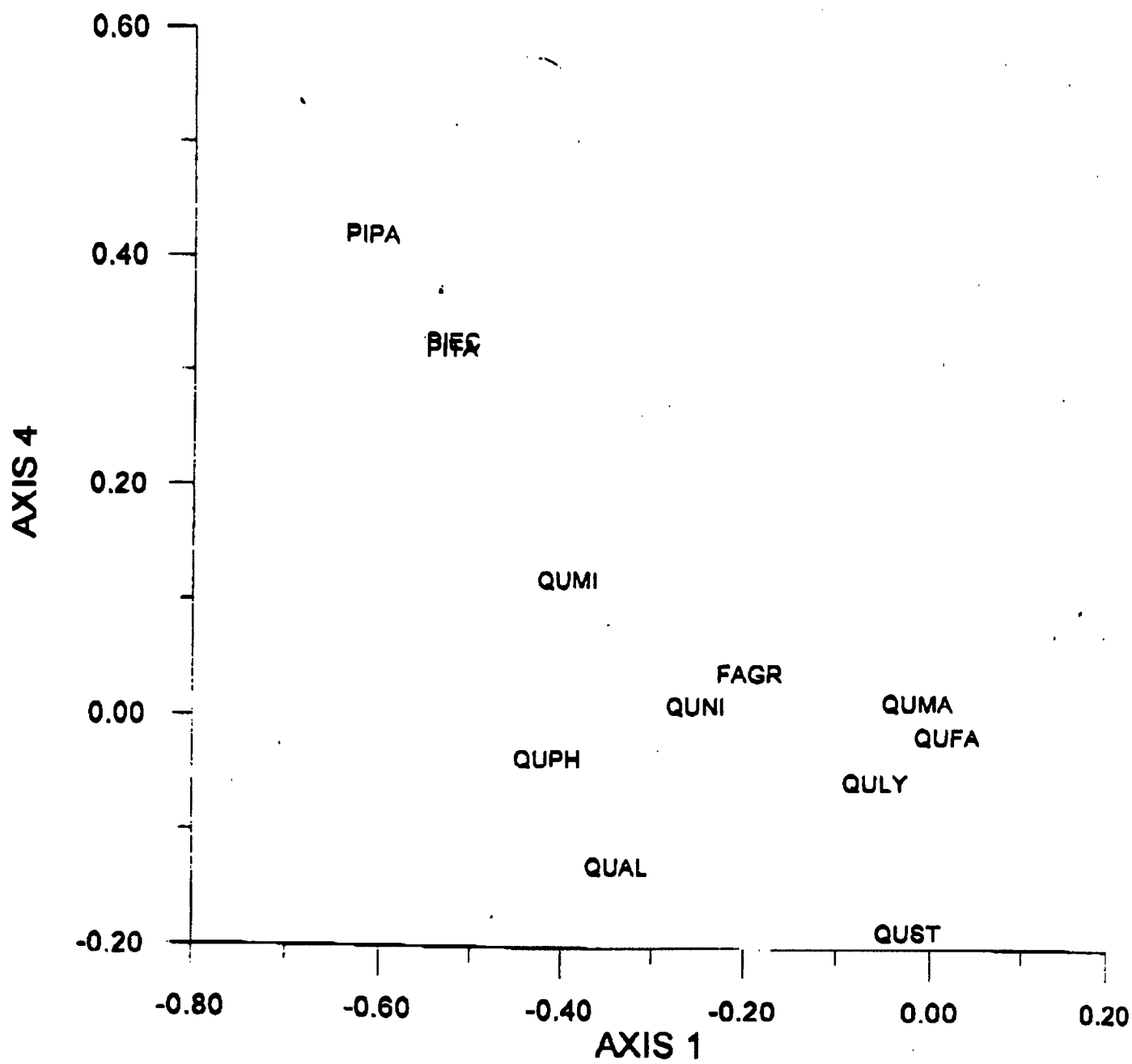


FIGURE 13

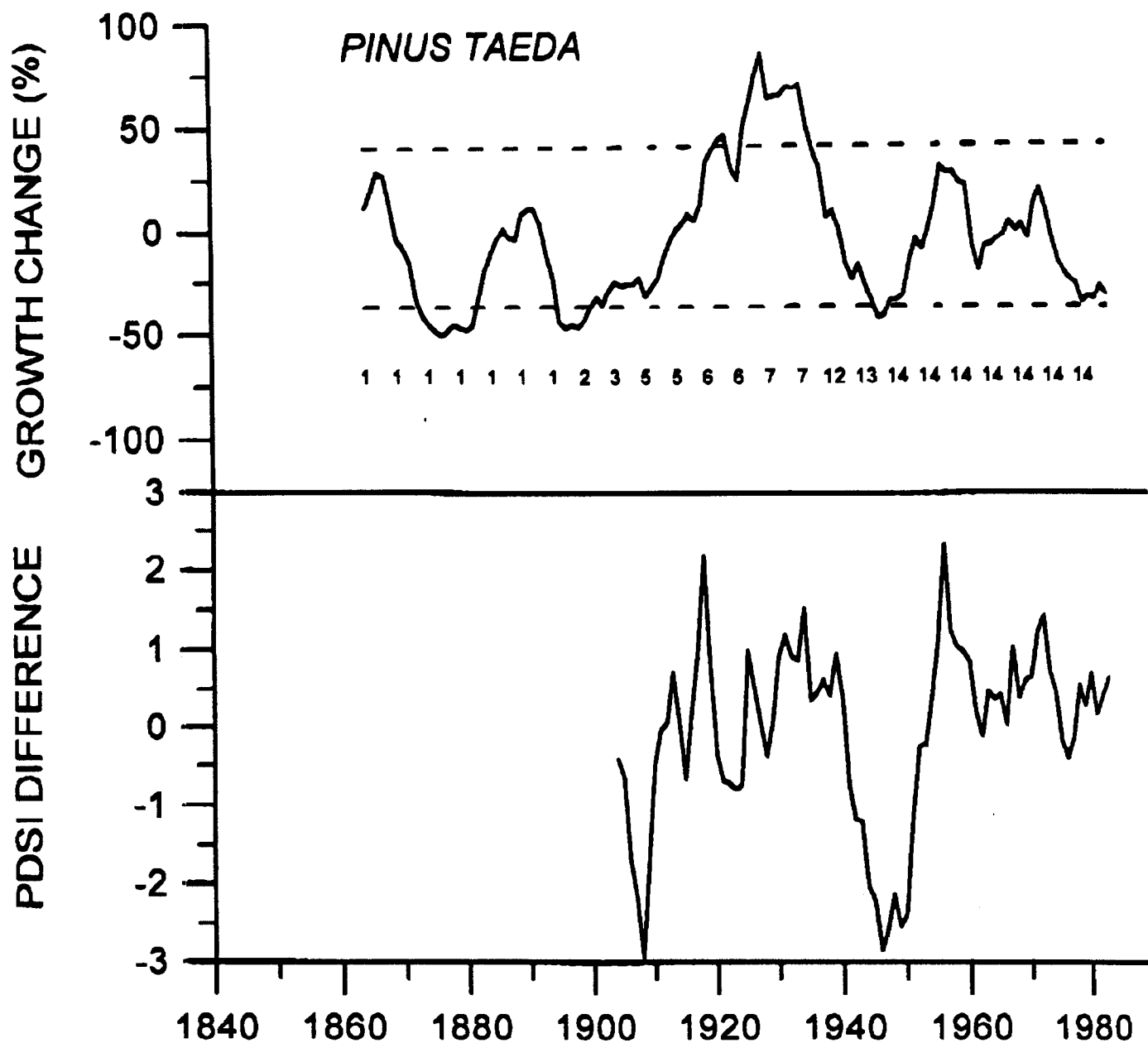


## Tree Rings and Climate Change: Final Report

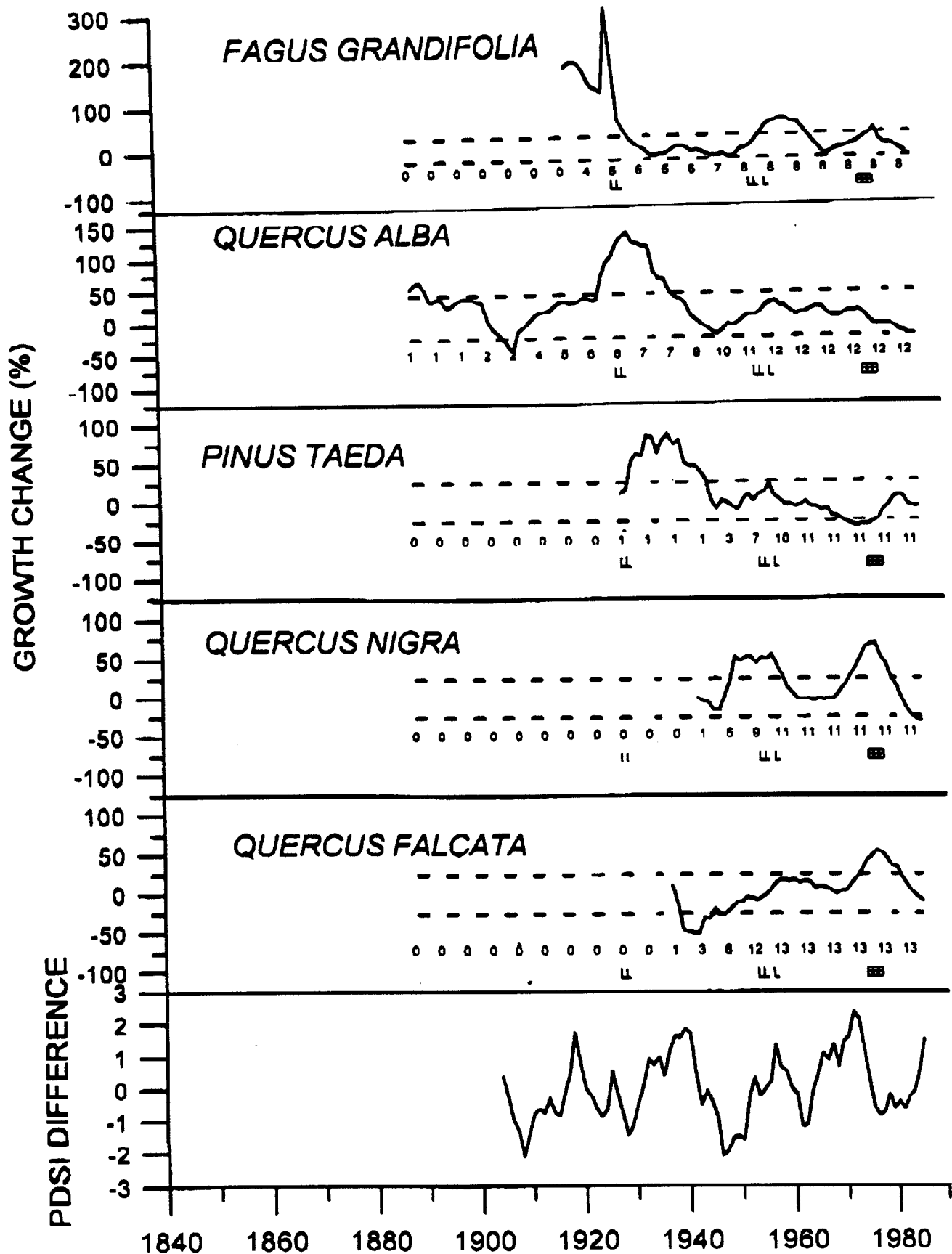
### APPENDIX A

Percent Growth Change (i.e. disturbance) chronologies for all stands and species listed alphabetically in order of stand name (longleaf chronologies are an exception, as noted below). Upper and lower dashed lines indicate thresholds of variation attributable to climate. Numbers below each graph indicate sample sizes (i.e. numbers of cores). Summer PDSI difference chronologies from the nearest climate grid point are shown for comparison below the tree-ring chronologies. "Substand labels" are provided in cases where different species within a site were cored in somewhat different locations. Note that longleaf chronologies are grouped together on two pages labeled "Longleaf I" and "Eastern Longleaf", respectively. For Beech Creek, dates of logging (L), and beetle defoliation (B) are also indicated.

# BASTROP STATE PARK



# BEECH CREEK UNIT (BIG THICKET NP)



The figure consists of five vertically stacked line graphs sharing a common x-axis representing years from 1840 to 1980. The y-axis for the top four graphs represents PDSI values, ranging from -50 to 150. The bottom graph represents the PDSI difference, ranging from -3 to 3.

- FAGUS GRANDIFOLIA:** Shows a sharp peak around 1855 (PDSI ~150) and another peak around 1885 (PDSI ~100). The data ends around 1900. Below the line are 18 small numbers (mostly 1s and 2s).
- PINUS TAEDA:** Shows two major peaks around 1910 (PDSI ~100) and 1925 (PDSI ~100). The data ends around 1950. Below the line are 28 small numbers (mostly 1s and 4s).
- QUERCUS ALBA:** Shows several peaks, with notable ones around 1855 (PDSI ~100), 1885 (PDSI ~100), and 1925 (PDSI ~100). The data ends around 1950. Below the line are 30 small numbers (mostly 1s and 2s).
- QUERCUS NIGRA:** Shows a peak around 1950 (PDSI ~40). The data ends around 1980. Below the line are 28 small numbers (mostly 1s and 2s).
- PDSI DIFFERENCE:** A line graph showing the difference in PDSI between the four species from 1900 to 1980. The values fluctuate between -2 and 2.