ANA CAROLINA MAIOLI CAMPOS BARBOSA

TREE-RING STUDIES OF METEOROLOGY, CLIMATE, AND FOREST ECOLOGY IN THE CENTRAL UNITED STATES

LAVRAS – MG
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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia Florestal, área de concentração Ciências Florestais, para a obtenção do título de Doutor.

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(ESTUDOS DENDROCRONOLÓGICOS DE METEOROLOGIA, CLIMA E ECOLOGIA FLORESTAL NOS ESTADOS UNIDOS CENTRAL)

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia Florestal, área de concentração Ciências Florestais, para a obtenção do título de Doutor.

APROVADA em 20 de dezembro de 2010.

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LAVRAS – MG

2010

“Pelo sopro de Deus se dá a geada, e as largas águas se congelam, também de umidade carrega as densas nuvens, nuvens que espargem os relâmpagos. Então elas, segundo o rumo que Ele dá, se espalham para uma e outra direção, para fazerem tudo que lhes ordena sobre a redondeza da Terra. E tudo isso faz Ele vir para disciplina, se convém à terra, ou para exercer a Sua misericórdia.” (Jó 37: 10-13). **Obrigada, Senhor, pelas maravilhas da Sua criação!** *“Ó profundidade da riqueza, tanto da sabedoria como do conhecimento de Deus! Quão insondáveis são os Teus juízos e quão inescrutáveis os Seus caminhos! Quem, pois, conheceu a mente do Senhor? Ou quem foi o Seu conselheiro? Ou quem primeiro Lhe deu a Ele para que Lhe venha a ser restituído?”* **A Jesus Cristo, meu Senhor e Salvador, tudo dedico e ofereço** *“porque Dele e por meio Dele e para Ele são todas as coisas. A Ele, pois, a glória eternamente. Amém” (Romanos 11: 33-36).*

“By the breath of God ice is given, and the broad waters are frozen. Also with moisture He saturates the thick clouds; He scatters His bright clouds. And they swirl about, being turned by His guidance, that they may do whatever He commands them on the face of the whole Earth. He causes it to come, whether for correction, or for His land, or for mercy.” (Job 37: 10-13). **Tanks, Lord for the beauty of Your creation!** *“Oh, the depth of the riches both of the wisdom and knowledge of God! How unsearchable are His judgments and His ways past finding out! For who has known the mind of the Lord? Or who has become His counselor? Or who has first given to Him and it shall be repaid to him?”* **I offer and dedicate everything to Jesus Christ, my Lord and Savior,** *“for of Him and through Him and to Him are all things, to whom be glory forever. Amen.” (Romans 11: 33-36).*

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A todos que contribuíram de alguma forma para a realização deste trabalho: MUITO OBRIGRADA!

“Bendito o homem que confia no SENHOR e cuja esperança é o SENHOR. Porque ele é como a árvore plantada junto às águas, que estende as suas raízes para o ribeiro e não receia quando vem o calor, mas a sua folha fica verde; e, no ano de sequidão, não se perturba, nem deixa de dar fruto.”

Jeremias, 17: 7-8

“Blessed is the man that trusteth in the LORD, and whose hope the LORD is. For he shall be as a tree planted by the waters, and that spreadeth out her roots by the river, and shall not see when heat cometh, but her leaf shall be green; and shall not be careful in the year of drought, neither shall cease from yielding fruit.”

Jeremiah, 17: 7-8

RESUMO GERAL

Registros dendrocronológicos de longo prazo podem oferecer evidências consistentes de como modificações no ambiente físico afetam a estrutura, dinâmica e funcionamento de ecossistemas. Esse trabalho é dividido em duas seções: 1) uma breve revisão de literatura e destacando a relevância da dendrocronologia para as ciências ambientais e do clima; 2) dois estudos independentes, na forma de artigos, com aplicações das técnicas dendrocronológicas para avaliar o registro de eventos climáticos. O primeiro artigo trata da cronologia de eventos de congelamento registrados nos anéis de crescimento de *Pinus aristata*, relacionando esses eventos a condições climáticas e meteorológicas. O objetivo deste trabalho foi construir um histórico de eventos de congelamento registrados nos lenhos inicial e tardio de árvores presentes no Pico *Goliath*, Colorado, ao longo de 60 anos. Os registros de congelamento presentes nos anéis foram analisados junto a dados diários de temperatura e de variáveis meteorológicas. O congelamento no lenho inicial foi mais comum que no tardio, indicando uma elevada ocorrência de baixas temperaturas no início da estação de crescimento; no lenho tardio o congelamento foi relacionado a menores temperaturas no verão que podem retardar o início e término do crescimento radial de *P. aristata* em altitudes elevadas. O mapeamento de características meteorológicas indicou a advecção de massas de ar frio associadas a episódios de congelamento severo desde 1952. O segundo artigo visou estudar a influência do clima nos padrões de crescimento radial de árvores, ao longo de um gradiente ambiental paralelo ao da vegetação, no centro-sul dos Estados Unidos. Séries cronológicas de anéis de crescimento de *Quercus stellata* foram selecionadas de 55 sítios em três ecossistemas: *Ozark oak-hickory forest, Cross Timbers* e *Post-oak Savanna*. Quatro bases de dados foram submetidas à análise de componentes principais (PCA) e PCA rotacionada (RPCA): (1) 55 cronologias de anéis de crescimento, (2) índice Z de Palmer para 44 pontos de grade correspondentes aos 55 sítios, (3) cronologias livres do sinal climático e (4) cronologias sem sobreposição, em períodos de 50 anos de 1751 a 1950. Em geral, o padrão de crescimento radial das árvores foi semelhante aos padrões dos índices de umidade de junho. Após a remoção do sinal climático, a distribuição espacial da variância pareceu estar associada à fenologia (sazonalidade da quebra de dormência de *Q. stellata*) e com a ocorrência de distúrbios (como tornados, queimadas e granizo). A análise dos períodos de 50 anos indicou que o padrão espacial de crescimento das árvores foi estável ao longo do tempo.

Palavras-chave: Dendrocronologia. Dendroecologia. *Pinus aristata*. *Quercus stellata*.

GENERAL ABSTRACT

Long-term dendrochronological records can offer substantial evidence on how changes in the physical environment affect ecosystems structure, dynamics and functioning. This work presents two sections: 1) a brief literature review showing the relevance of dendrochronology to climate and environmental sciences; 2) two independent studies with different applications of dendrochronological techniques to address the effects of climate in trees. The first article deals with event chronology of frost-rings in high altitude bristlecone pines and the relation of these events with meso-scale meteorological and climatic conditions. This research aimed to develop an unbiased record of early and latewood frost-rings in high altitude bristlecone pines (*Pinus aristata*) at Goliath Peak, Colorado, during the last 60 years. To determine the climatic significance of the frost-ring records, daily temperature data and composite mapping of weather features were analyzed. Earlywood frost-rings were far more common than latewood frosts at Goliath Peak and represented highly unusual late-season outbreaks of severe subfreezing temperatures early in the growing season. Latewood frosts were related with below average summer temperatures that could have delayed both the onset and termination of radial growth in high elevation bristlecone pines. Composite mapping of weather features document the large-scale advection of cold air masses associated with severe frost episodes since 1952. The second article consisted in a dendroclimatic approach to evaluate how climate affects radial growth patterns across an environmental gradient that parallels the vegetation continuum in the southcentral United States. Tree-ring chronologies from post oak (*Quercus stellata*) were selected from 55 sites comprising three major ecosystems: Ozark oak-hickory forest, Cross Timbers, and Post-oak Savanna. Four data sets were analyzed using principal components analysis (PCA) and rotated PCA: (1) 55 tree-ring chronologies, (2) Palmer Z-indices for the 44 grid points closest to each of the 55 tree-ring sites, (3) climate “signal free” tree-ring chronologies, and (4) tree-ring chronologies for non-overlapping 50-yr sub-periods from 1751-1950. The major spatial patterns of tree growth indeed resembled the major patterns of June moisture balance. After removing climate signal a considerable amount of residual variance was still left over and appeared to be related with plant phenology (seasonal onset of growth) and disturbance (such as tornado, fire, and ice storms). A temporal analysis conducted with four 50-yr sub-periods showed that the spatial patterns of tree growth variation appeared to be stable over time.

Keywords: Dendrochronology. Dendroecology. *Pinus aristata*. *Quercus stellata*.

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1 INTRODUCTION

A fundamental question environmental scientists throughout the world are facing is how climate change could affect terrestrial ecosystems, impacting over environmental resources and services at local to global scales (McMULLEN; JABBOUR, 2009). Yet without substantial time series of climate and its effects on vegetation, any postulation concerning climate change and any attempts at forecasting impacts and feedbacks remain essentially speculative. This lack of knowledge makes it difficult for conservation managers and planners, climatologists and ecologists to proactively define future climatic scenarios and estimate the potential impacts of climate changes over natural resources (LILLY, 1977; ROZESNWEIG et al., 2008; SOLOMON et al., 2007).

Although knowledge of the likely consequences of climate changes over terrestrial ecosystems is yet scarce, long-term dendrochronological records can offer substantial evidence on how changes in the physical environment affect ecosystems structure, dynamics and functioning. Registered vegetation responses to historical climate variability include shifts to earlier onset of spring events such as leaf unfolding, blooming date, and reproduction timing, change in species distribution, and modification of community structure (McMULLEN; JABBOUR, 2009; ROSENZWEIG et al. 2008).

The science of dendrochronology may be broadly defined as the study of yearly growth patterns in trees and their use in dating past events and in evaluating fluctuations in past climate (FRITTS, 1966). Tree-ring chronologies are a valuable source of high resolution proxy climate data for the past few centuries, and can offer improved estimate of the long-term mean, variance, and trend of important climate variables such as temperature and precipitation (FRITTS; SWETNAM, 1986). By knowing environmental conditions that operated in the past, climatologists and environmental scientists can develop more adequate models of climate system in order to forecast spatial-temporal patterns of vegetation responses to future scenarios (BRIENEN et al., 2010; ROSENZWEIG et al., 2008).

Within this frame a brief literature review is presented in this first section, and aims to highlight the relevance of dendrochronology to climate and environmental sciences, the principles and techniques involved in tree-ring studies, and some examples of the diverse applications of tree-ring research. A topic is dedicated to “dendrochronology in the tropics” and was included to expose the potential and challenges involved in developing dendrochronological researches on tropical trees. The first section ends with a general summary presenting the main results obtained.

After the previous background, the second section presents two independent studies developed during an internship at the Tree-ring Laboratory of the University of Arkansas, Fayetteville. These studies are presented in a standard article format and deal with different applications of dendrochronological techniques to address the effects of climate in trees. The first article deals with event chronology of frost rings in high altitude bristlecone pines and the relation of these events with meso-scale meteorological and climatic conditions. The second article searches for tree growth spatial and temporal patterns across an environmental gradient in the southcentral United States.

2 LITERATURE REVIEW

A brief literature review is shown highlighting the relevance of dendrochronology to climate and environmental sciences.

2.1 Dendrochronology and related fields

Andrew E. Douglass, an astronomer working in Arizona, is credited with developing tree-ring dating and is considered the father of the discipline of dendrochronology. *Dendro* refers to the Greek root word meaning tree, and *chronology* refers to time. The discipline is characterized as the systematic use of tree-ring crossdating, which involves matching the patterns of ring-width variations through time in the sampled trees to establish the exact year in which each ring was formed (DOUGLASS, 1941; FRITTS; SWETNAM, 1986). With the development of crossdating by the beginning of the past century, a scientific basis existed to prove the annual nature of tree-rings from temperate regions (WIMMER, 2002). Therefore, crossdating is considered the most significant technical discovery made by Douglass and was extensively used in his astronomical, archeological, and climatic research (DOUGLASS, 1927, 1929).
Tree-ring dating is considered to be the most accurate and precise dating method in geochronology (STAHLE; FYE; THERRELL, 2003). Among its attributes, tree-ring chronologies present annual resolution that can be precisely placed in time, and can be easily obtained by measuring the ring-widths for a continuous sequence of years. Few other sources of paleoclimatic information can provide both continuity and precise datability, and few can be replicated and quantified as easily as tree-rings (FRITTS, 1976). Dendrochronology has been routinely used to exactly date past climatic variation (FRITTS, 1966; SALZER; KIPFMUELLER, 2005), archeological sites (DOUGLASS, 1929), geomorphic and tectonic processes (LA MARCHE, 1961), fire history (SWETNAM, 1993), frosts events (MOCK et al., 2007), and other environmental events over the past few hundred to few thousand years.

When dendrochronological techniques are applied to a specific problem or field (e.g. climate, environment) it is common to use the prefix *dendro* in conjunction with the name of the particular scientific discipline (e.g. climatology, ecology). This way, *dendroclimatology* refers to dendrochronological investigations of past and present climates. Likewise, *dendroecology* refers to the application of dendrochronology to the study of the ecology of past biotic communities (FRITTS, 1976; FRITTS; SWETNAM, 1986). Consequently, dendrochronology can be divided into a number of subfields depending on the focus of its application, and other terms may emerge, such as: *dendrohydronlogy* (reconstruction of river flow and flooding histories), *dendrogeomorphology* (geomorphic processes), *dendropyrochronology* (reconstruction of forest fires), among many others. The choice of the identifying term is arbitrary and many dendrochronological studies may fall into more than one of these subfields.

2.2 Methods of dendrochronology: principles and techniques

Douglass' method of crossdating was the first of a number of techniques and basic dendrochronological criteria to be adopted in tree-ring dating. These criteria have been described by Fritts (1971, 1976) in the following interconnected principles briefly described here:

1) The *uniformitarian principle* implies that the physical and biological processes which link the environment with the variation of tree growth must have been in action in the same ways in the past as in the present. Thus, one can establish the relationship between variations of tree growth and variations in present climate and infer from past rings the nature of past climate.
2) The *principal of limiting factors* is a well-known biological law which states that a biological process (e.g., tree growth) cannot proceed faster than is allowed by the most limiting factor (e.g., moisture). This is very important

to dendrochronology because if the growth of a tree is never limited by some climatic or environmental condition, there will be no information on climate in the widths of rings and they will not crossdate.

3) The *principal of site selection* supports the stratified sampling in which the dendrochronologist searches for a population of ring-widths which contains the desired information. The selection involves limiting the sampling space to a small number of variables relevant to the question in hand (e.g., in studies of ring-width and drought, it is important to rely upon arid-site trees where rind-width is most likely to have been limited by moisture availability).

4) The *principal of sensitivity* has to do with the variation in width from one ring to another, and is intimately connected with the two previous principles. The more the tree has been limited by environmental factors, the more variability in ring-widths will be observed. This variability is referred to as *sensitivity*, while the lack of ring-width variability as *complacency*.

5) *Crossdating* was defined by Douglass (1941) as the recognition of the same ring pattern in different trees, so that the actual growth date of any one ring of the pattern is the same in the different trees and one may carry a chronology across from tree to tree. This principle is based on the presence of a limiting factor influencing over the growth of all trees of the same species in a given area and producing synchronous variations in ring-widths.

6) The *principle of replication* is implied in the principal of crossdating a large number of samples from several trees in a given area. Not only does the principle ensure the collection of a statistically representative sample but it also guarantees the accuracy of the crossdating. Repetition or replication in sampling includes the number of radius per tree and the number of trees.

7) *Standardization* is a basic procedure in dendrochronology and consists in removing systematic changes in ring-width associated with age and geometry of the tree. Growth increments generally become narrower as the tree ages and the rings in the outer portion of the stem extend around a larger circumference (FRITTS, 1966). After standardization, measured raw ring-widths are transformed into *ring-widths indices* values.

A linear aggregate model (Equation 1) was proposed to decompose the signal in tree-rings into an aggregate of environmental factors, both natural and human (FRITTS; SWETNAM, 1986). In order to extract the desired environmental signal being studied, the other factors should be minimized.

$$Rt = Gt + Ct + \delta D1t + \delta D2t + \delta Pt + Et \qquad (1)$$

where:

R: each ring width assumed to have been accurately dated to the year *t;*

G: the age related growth trend value in year *t;*

C: the climatically related growth variations in year *t;*

D1: occurrence of endogenous disturbance pulse (e.g., competition)*;*

D2: occurrence of exogenous disturbances pulse (e.g., fire, ice storm)*;*

P: pollutant effects that impact radial growth in year *t;*

E: random processes (error) in year *t;*

δ: binary indicator of presence (δ =1) and absence (δ =0).

These major principles of dendrochronology provide the basis of the standard methods developed for conducting reliable tree-ring research and have been described in detail (FERGUSON, 1970a; FRITTS, 1976; STOKES; SMILEY, 1968). The standard techniques include collecting adequate field data, laboratorial procedures (specimens preparation, crossdating, ring-widths measurements) and time series analysis (general statistics, standardization, correlation analysis, among others).

Sampling may be done by taking a cross section or by using a Swedish increment borer, a precision tool designed to remove a small core without causing much harm to the living tree (Figure 1). Increment cores can be transported to the laboratory using straws or corrugated cardboard sections. It is vital to obtain complete field notes with information about sampled trees and sites (FERGUSON, 1970a; FRITTS, 1976). Records of slope, exposure soil, plant community characteristics, and obvious site disturbance can be used to account for unusual results or to select data to test future hypotheses.

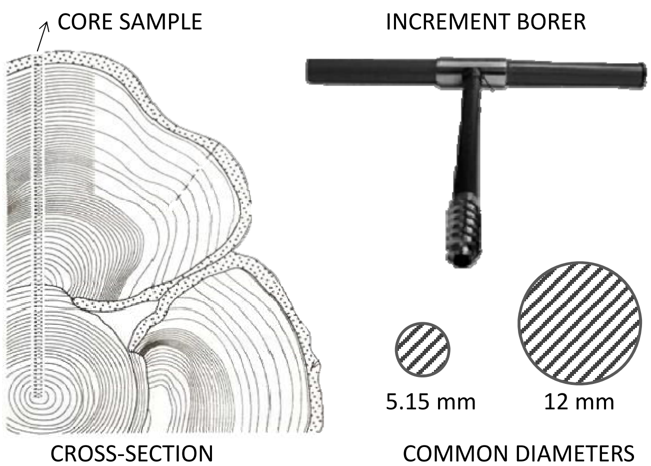

Figure 1 Schema showing cross-section and core sample types on the left (VILLALBA, 2000), and an increment borer on the right. The tip of the borer has a razor-sharp cutting edge with external screw threads that draws the borer into the trees as the handle is turned

The cores and cross-sections should be air-dried before receiving surface treatments. The cores are mounted in a wooden support (mount) to enable further handling and storage. Transverse surface of both cross-sections and cores are sanded with progressively finer textures of sandpaper (e.g., 180, 220, 320, 380, 400 or 600), depending upon the quality of the cut surface and the hardness of the wood (STOKES; SMILEY, 1968). Proper surfacing is an absolute prerequisite in order to accurately observe minute anatomy of xylem cells under magnification ranging from 10X to 70X (STAHLE, 1990).

The crossdating procedure, in practice, involves detecting and correcting for any lack of synchrony due to missing rings, or simple errors in observation or counting (FRITTS; SWETNAM, 1986). The Skeleton plot is the most simple and successful method for crossdating and is based on a careful examination of each specimen under the microscope and assigning the rates of narrow and wide rings to reveal the major patterns of ring-widths (STOKES; SMILEY, 1968). After all corrections are made the dating is marked on the specimen by making a pinhole on each decade ring, two on the half centuries, and three on the centuries (FERGUSON, 1970a; STOKES; SMILEY, 1968). The ring sequence of each dated specimen are then measured to obtain a single tree-ring chronology and submitted to quality control to check for crossdating and overall quality using the software COFECHA (HOLMES, 1983).

The individual tree-ring chronologies are standardized to remove growth trend before further time series analysis and climate correlation. An exponential growth trend curve is fitted to the data and the ring-widths are standardized by dividing each one by the value of the fitted curve (FRITTS, 1976; STOKES; SMILEY, 1968). After the removal of the association with ring-age, the transformed values are called ring-indices. The single time series of ring-indices from each core are finally averaged into one chronology for the study site and is namely a climate proxy.

2.3 Achievements and applications

Dendrochronology, as an established technique, has been applied in numerous and diverse fields. It is through this diversification of the tree-ring analysis method that the value and importance of the technique has become apparent to researchers throughout the world. The information gained through the science of dendrochronology can be used not only by climatologists, but also by researches interested in related environmental problems.

To the date more than 2000 chronologies have been constructed over six continents and are available at The International Tree-Ring Data Bank (2010), maintained by the NOAA Paleoclimatology Program and World Data Center for Paleoclimatology. The data bank includes raw ring width or wood density measurements, and site chronologies (growth indices for a site) last updated in February 2010.

The longest chronology, constructed by Ferguson (1970b) from *Pinus logaeva*, extends back for more than 8,000 years and has proved to be so accurate that it has been used to recalibrate the radiocarbon time scale. A 7,100-year tree-ring chronology from *Pinus aristata* Engelm in the White Mountains of east-central California has demonstrated the extreme value of these forest relics of truly ancient bristlecone pine trees (FERGUSON, 1968). Field work across North America has helped to find large tracts of ancient forest that were present before European settlement on the New Land and have escaped from the common destiny of their cohorts (STAHLE, 1996). These old growth remnants offer a unique quantitative means to extend short term observations into the past hundreds years (FRITTS, 1976).

Specific events can be dated by unusual ring features or evidence of injury such as: cell collapse, wounds, callus tissue, compression wood, and abundant resin duct formation, among others (FRITTS; SWETNAM, 1986; WIMMER, 2002). Determining the frequency of such events and their relation with other environmental processes has brought many insights to environmental sciences. To give only few examples, long histories of wildfires have been developed on the basis of tree-ring dated fire scars within trees (MARGOLIS; SWETNAM; ALLEN, 2007; SWETNAM, 1993) and have been linked to moisture anomalies with the El Niño-Southern Oscillation phenomenon (SWETNAM; BETANCOURT, 1990). Frost injuries within annual rings have been used to identify years of unusual early-season frost (JACOBY; WORKMAN; D'ARRIGO, 1999; LA MARCHE; HIRSCHBOEK, 1984; MOCK et al., 2007; YAMAGUCHI, 1993; YAMAGUCHI; HOBLITT, 1995), some of which were associated with major volcanic eruptions that may eject dust and ash into the upper atmosphere causing macro-scale cooling.

Another general application of dated tree-ring information to environmental problems is to reconstruct past variations in drought (COOK et al., 1999, 2007, 2010), temperature and precipitation (BRIFFA et al., 1990; SALZER; KIPFMUELLER, 2005; STAHLE; HEHR, 1984), stream flow and water levels (BÉGIN; PAYETTE, 1988; COOK; JACOBY, 1983). This type of dendrochronological application is very important and needed because the existing instrumental climate data are too short to detect long term climatic variability and change. Tree-rings have also demonstrated to be sensitive to global increase in carbon dioxide (COOK et al., 1996; KNAPP; SOULÉ; GRISSINO-MAYER, 2001) and continue to be a potential tool for the global carbon budget assessment.

2.4 Dendrochronology in the tropics

Dendrochronology in the tropics did not have the same evolution as in temperate region of high altitudes. Although seasonal periodicity in growth and flowering is a common phenomenon in tropical regions, there is still much uncertainty as to the factors controlling this periodicity because tropical climates are often regarded as nonseasonal (ALVIM, 1964). Seasonal phenology phases in regions with fairly uniform rainfall distribution have been attributed to "inherent rhythm" as a trigger for unexplained periodical growth processes. One of the most important reasons for the low acceptance of seasonal tree growth in the tropics is the focus of dendrochronology, eco-physiology and wood formation based on the conditions encountered in the temperate zones (WORBES, 2002). Another reason is the fact that the majority of tropical trees do not shows annual growth rings such as is found in temperate zone trees (STAHLE, 1999; WORBES, 2002), although a relatively high proportion of species showing clear demarcation of radial growth activity have been documented (ALVES; ANGYALOSSY-ALFONSO, 2000; BAAS; VETTER, 1989).

The work of Mariaux (1970) in West African countries was one of the milestones of tropical tree-ring research. He used cambial wounding, known as *Mariaux's windows*, to prove annual wood growth of important timber species. Other findings of this kind triggered a new period of growing interest in tropical dendrochronology by the end of last century, marked by three international meetings. The first workshop under the theme "Age and Growth Periodicity in Tropical Trees" (BORMAN; BERLYN, 1981), was held in 1980 in New Heaven when new directions for research were identified. The results were presented during a second meeting in São Paulo (BASS; VETTER, 1989) and a third in Kuala Lumpur, Malaysia (ECKSTEIN; BASS, 1995). The impact of these workshops can be verified by the increased relevance of tree-ring research in the tropics.

Worbes (2002) divides the development of tropical dendrochronology into three overlapping research fields: (1) verification and description of the nature of growth periodicity in the tropics, (2) investigations on growth-climate relations of tropical trees, and (3) examination of growth and dynamics of natural forests. Most of the published literature belongs to the first category, with descriptive nature and little climatological explanations. As a result, various lists of suitable species for tree-ring analysis are available for different regions of Africa (AMOBI, 1973; DÉTIENNE, 1989; ESHETE; STAHL, 1999), Central America (DREW, 1998), the Brazilian Amazon and deciduous forests (VETTER; BOTOSSO, 1989; LISI et al., 2008; WORBES, 1989, 2002), Australian tropics (ASH, 1983; OGDEN, 1981), and southeast Asia (ASH, 1986). Alves and Angyalossy-Alfonso (2000) recorded the presence of distinct growth rings in 48% of 491 Brazilian tree species (133 genera and 22 families). These lists of suitable species for tree-ring chronology still need rigorous confirmation by dendrochronological methods. In fact, dendrochronology is one of the best strategies to test the annual nature of growth banding in tropical species (STAHLE, 1999). Crossdating among trees in a given region can provide strong evidence of synchronized growth periodicity.

The investigations on growth-climate relations of tropical trees can be attributed to two mechanisms inducing cambial dormancy in tropical trees: seasonal rainfall and flood pulses. Dry tropical forests with several months of drought (e.g., savannas, deciduous and semi-deciduous forests) and annual flooding (e.g., wetlands and flooded forests of central Amazon) have been confirmed to induce cambial dormancy recorded in the growth rings of some tropical trees (WORBES, 1989). In tropical areas subjected to seasonal drought clear correlation between growth and precipitation has often been established (BRIENEN et al., 2010; ENQUIST; LEFFLER, 2001; STAHLE et al., 1999). Annual long-term flooding along the Amazon River has been shown to trigger growth periodicity in many tree species (SCHÖNGART et al., 2002) allowing the construction of tree-ring chronology (SCHÖNGART et al., 2004). Climatological oriented tree-ring research in the tropics have shown to be sensitive to the El Niño-Southern Oscillation (ENSO) (BRIENEN et al., 2010; ENQUIST; LEFFLER, 2001; SCHÖNGART et al., 2004) and could provide reliable information related to the intensity and frequency of past ENSO events.

The examination of growth and dynamics of natural forests using tree-ring standard methods could have great impact to conservation and ecological sustainable management of tropical forests. Up till now, growth patterns of commercial timber-producing species exist for only two sites in Africa (STAHLE et al., 1999), one in the Bolivian Amazon (BRIENEN; ZUIDEMA, 2006), and lowland areas of central Amazon, Brazil (SCHÖNGART, 2008). Increment estimations are also necessary for computing carbon uptake by managed and undisturbed natural forests in connection with the Kyoto protocol (WORBES, 2002). Dendrochronology studies on vegetation dynamics and successional patterns of natural forest stands are still scarce, but some efforts have demonstrated the value of such researches (WORBES et al., 2003).

In Brazil, with the exception of the above mentioned recent achievements for the central Amazon region, tree-ring research is still considered to be incipient. Tree-ring analyses were used to study the radial growth and periodicity in the Atlantic Rain Forest (CALLADO et al., 2001), formation of annual rings in semi-deciduous forest from the southeast (LISI et al., 2008; TOMAZELLO FILHO et al., 2004) and mixed forest from the southern region (OLIVEIRA et al., 2009; SEITZ; KANNINEN, 1989). No significant contributions were found to the second largest Brazilian biome, *Cerrado* (Brazilian savanna), or Caatinga (scrubby woodland). Tropical forests will experience relatively large changes in temperature and rainfall towards the end of this century due to global climate changes (BRIENEN et al., 2010). Yet, there is a clear information gap to predict the behavior of our ecosystems in response to future environmental scenarios. The lack of consolidated national tree-ring network collaboration contributes to the delay in the development of consistent dendrochronological researches.

3 GENERAL SUMMARY

This thesis is the result of two independent studies that represent my introduction into the field of dendrochronology. During the visit to the Tree-ring Laboratory of the University of Arkansas, I was trained by Dr. David W. Stahle to conduct tree-ring research by applying standard dendrochronological techniques that can guarantee high quality, robust, and reliable tree-ring data. The construction of this knowledge is far from complete, and the present work is just a first step to introduce the discipline of dendrochronology to the *Universidade Federal de Lavras*. There is definitely a tremendous potential for tree-ring research on the Brazilian ecosystems and dendrochronology techniques could contribute to multi-disciplinary problems related to forest sciences (e.g., climate change, ecology, and management).

The first article entitled "*The synoptic meteorology of early and late-season frosts recorded by bristlecone pine trees at Goliath Peak, Colorado*" was written with the collaboration of David W. Stahle, Matt Bunkers, Ed Cook, Gregg Garfin, and Ricardo Villalba. An unbiased record of early and latewood frost-rings in high altitude bristlecone pines at Goliath Peak, Colorado, was developed for the last 60 years. Frost-rings occurred with an expressive high frequency at Goliath Peak, Colorado, and could be one of the most frost-sensitive site location ever registered. Earlywood frost-rings represented highly unusual late-season outbreaks of severe subfreezing temperatures early in the growing season events. Latewood frosts were related with below average summer temperatures that could have delayed both the onset and termination of radial growth in high elevation bristlecone pines. Composite mapping of weather features document the large-scale advection of cold air masses associated with severe frost episodes since 1952.

In the second article, "*A spatial and temporal analysis of tree growth and climate in the southcentral United States*", the major spatial patterns of post oak growth resembled the major patterns of June moisture balance. When June soil moisture climate signal was removed from tree-ring time series, a considerable amount of residual variance was still left over and appeared to be related with plant phenology (post oak seasonal onset of growth) and disturbance (such as tornado, fire, and ice storms). A temporal analysis conducted with a 200-yr time span (1751-1950) showed that the spatial patterns of tree growth variation appeared to be stable over time.

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ARTICLE 1: The synoptic meteorology of early and late-season frosts recorded by bristlecone pine trees at Goliath Peak, Colorado

Illustration by **Fred Paillet**, Geosciences Department, University of Arkansas

ABSTRACT

Previous studies have demonstrated the connection between frost-ring records and large-scale climate anomalies in the western and southcentral United States. These anomalies seem to be related to internal and external climate forcing factors such as El Niño-Southern Oscillation, Pacific /North American circulation patterns and volcanic eruptions. However, the large-scale meteorological environment responsible for frost-rings in the springwood of bristlecone pine has not been described in detail. Therefore, this research intended to develop an unbiased record of early and latewood frost-rings in high altitude bristlecone pines (*Pinus aristata*) at Goliath Peak, Colorado, during the last 60 years. Daily maximum and minimum temperature were examined to determine the climatic significance of the bristlecone pine frost-ring record. Composite mapping of weather features were used to document temperature anomalies associated with severe frost episodes since 1952, following the description of the synoptic meteorological conditions responsible for these unusual growing-season temperatures at high elevation sites in the central Rocky Mountains. All earlywood frost-rings occurred during highly unusual early growing season freeze events in Colorado Rockies associated with the penetration of a deep upper level low pressure system into the central United States. Only three latewood frost-rings were contemporaneous with nearby daily meteorological data, but the early fall freezings associated with all three were the beginning of persistently cooler autumn temperatures.

Keywords: Dendrochronology. Frost rings. *Pinus aristata.*

RESUMO

Alguns estudos demonstram a relação entre o registro de eventos de congelamento em anéis de crescimento de árvores e a ocorrência de anomalias climáticas de larga escala nas regiões oeste e centro-sul dos Estados Unidos. Essas anomalias parecem estar relacionadas com a ocorrência de fenômenos externos, como El Niños, alterações dos padrões de circulação atmosféricas no Pacífico Norte e erupções vulcânicas. Contudo, os padrões meteorológicos relacionados ao congelamento de anéis formados na primavera, em *Pinus aristata*, não foram ainda descritos em detalhes. Diante disso, estudou-se registros de anéis de crescimento em lenho inicial e em lenho tardio nessa espécie, em condições de elevada altitude (Pico *Goliath*, no Estado do Colorado) ao longo dos últimos 60 anos. Valores máximos e mínimos diários de temperatura foram examinados junto aos registros de anéis de crescimento e mapas de características meteorológicas foram utilizados para documentar anomalias de temperatura associadas aos eventos de congelamento desde 1952, seguindo a descrição sinótica das condições meteorológicas responsáveis pelas condições anormais durante a estação de crescimento. Todos os registros de congelamento do lenho inicial foram associados a temperaturas atípicas no início da estação de crescimento, caracterizada pela formação de um sistema de baixa pressão na região central dos Estados Unidos. Apenas três registros de congelamento no lenho tardio foram observados, sendo os três associados com um decaimento persistente da temperatura no outono.

Palavras-chave: Dendrocronologia. Congelamento em anéis. *Pinus aristata.*

1 INTRODUCTION

Frost damage to the annual growth rings of several tree species are known to be an indicator of unusual subfreezing temperatures during the growing season. Previous studies in the western and southcentral United States have demonstrated the connection between frost-ring formation and large-scale temperature anomalies (LA MARCHE; HIRSCHBOECK, 1984; STAHLE, 1990). These growing season temperature anomalies appear to be linked in some cases to internal and external climate forcing factors such as the El Niño-Southern Oscillation (ENSO) and large magnitude volcanic eruptions. While the unusual growing season circulation and temperature regimes responsible for frost-ring formation in trees may be the product of multiple causes, the synoptic meteorology of freeze events appears to be highly consistent from one frost event to another (STAHLE, 1990).

Climatic significance of latewood frost-rings in Great Basin and Rocky Mountain bristlecone pines has been addressed by La Marche and Hirshboeck (1984) and Brunstein (1996), respectively. However, the large-scale meteorological environment responsible for frost-rings in the springwood of bristlecone pine has not been described in detail. If consistent meteorological conditions are associated with these damaging late-season freeze events, then these meteorological conditions can be inferred from prehistoric frost-rings in millennia-old bristlecone pine trees. Dendrometeorological inferences of this nature have not been widely attempted, but can provide reasonable proxy information on short-term mesoscale weather events useful for investigating the atmospheric impacts of well-dated volcanic eruptions, ENSO extremes, or other climate forcings in prehistory.

The active cambium is especially susceptible to injury when temperatures drop below freezing, producing distorted xylem tissue referred to as frost-rings (FRITTS, 1976). Two types of frost-rings can be distinguished: earlywood frost-rings and latewood frost-rings. The first consists in a frost damage that occurs near the beginning of the growing season, and occurs in the first formed xylem cells of the annual ring. Earlywood frost-rings are also called spring-frost and late-season frost and in some cases can be linked with “false spring” events (warm late winter and spring conditions followed by an unseasonable late outbreak of freezing temperatures). On the other hand, latewood frost damage (also known as fall-frost and early-season frost) is formed near the end of the growing season and is believed to induce cambial dormancy due to early-season freezes (GLERUM; FARRAR, 1966). The anatomical features of frost-rings in conifers are diagnostic of extracellular freeze damage, and include deformed and underlignified tracheid cells, collapsed cell walls, discolored cell contents, and disrupted rays (BRUNSTEIN, 1995; GLERUM; FARRAR, 1966).

The freeze damage is triggered by the formation of ice in the intercellular spaces causing cell dehydration and external pressure on immature cambial cells and differentiating tracheids (GLERUM; FARRAR, 1966). One day of about freezing temperatures between two nights with temperatures down to -5 ^{o}C is sufficient to cause frost injury during the period of active cambial growth in trees (GLOCK; REED, 1940). Frost-rings are less frequently found in larger stems than in small branches, probably due to the insulation of the thick bark in old portions of the tree (FRITTS, 1976). Because young and vigorous trees often experience a longer growing season than mature to old-growth trees, they are potentially more vulnerable to late and early-season freeze damage (STAHLE, 1990).

The Rocky Mountain bristlecone pines (*Pinus aristata* Engelm.) are native to parts of Colorado, New Mexico, and Arizona. They are related to the Great Basin bristlecone pines (*P. longaeva*) and to foxtail pines (*P. balfouriana*), both native to the southwestern United States (BRUNSTEIN, 2006), and can be distinguished from them by numerous white resin specks present on the needles of the Rocky Mountain bristlecone pines. In this paper, bristlecone pine (*P. aristata*) trees growing at ~3500 meters on Goliath Peak, Colorado, were used to develop a chronology of frost-rings representing early and late-season freeze events. This chronology may provide an unbiased record of most freeze events during the last 60 years which were sufficiently intense to cause anatomical injury to multiple trees at Goliath Peak. We then describe the synoptic meteorological conditions responsible for these unusual growing-season temperatures at high elevation sites in the central Rocky Mountains.

2 SITE DESCRIPTION

The study site is located on Goliath Peak in the central Rocky Mountains (39°N 105°W: 3758 m.a.s.l.) near the northern limit of the bristlecone pine range in Colorado. The collection site was chosen on south- and south-east exposures near the alpine treeline (Figure 1), located east of the Mt. Evans highway, on the lower slopes of a glacially sculpted cirque, and along the edge of a hanging valley. Cold air drainage has depressed the bristlecone pine-dominated treeline some 200 meters down to the lip of the hanging valley (Figure 1). The soil was thin, well drained, and derived from granitic parent material.

3 METHODS

Increment cores were extracted nondestructively from living bristlecone trees using Swedish increment borers. Two collections were used to compile the data, the first collection was obtained during the Third Annual North American Dendroecological Fieldweek, held in 1992 (BUNKERS et al., 1992), and was updated with a second collection from a field expedition in September, 2010. To ensure that the derived frost-ring chronology accurately represents all freeze events sufficiently severe to damage trees, both field collections were mainly concentrated on "young" trees in the 50 to 100-year age class.

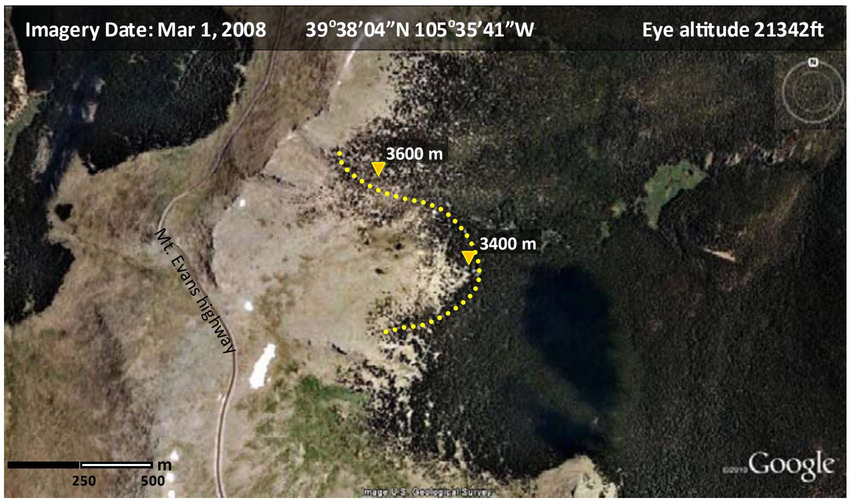

Figure 1 Satellite image from the site location near Goliath Peak, Colorado. The yellow dotted line east of the Mt. Evans highway indicates the inverted treeline depressed by cold air drainage 200 meters down to the lip of the hanging valley. Source: GOOGLE EARTH, 2010

Standard dendrochronological techniques were used to prepare and date the core specimens. All cores were dried, mounted, polished, and then crossdated using the methods described in Stokes and Smiley (1968). After the exact annual dates were determined for all growth rings, the years with anatomical evidence for frost injury were recorded for all specimens. Frost-rings occur in both the earlywood (springwood) and latewood (summerwood) portions of bristlecone pine growth rings at Goliath Peak, and represent freeze damage during late-season (spring) and early-season (fall) frosts, respectively. These frost-ring characteristics are visually apparent on polished radial surfaces at magnifications between 10X and 70X and are helpful in crossdating increment cores from bristlecone pines (BRUNSTEIN, 1996). Figure 2 shows four examples of earlywood (Figure 2A and B) and latewood frost injuries (Figure 2C and D).

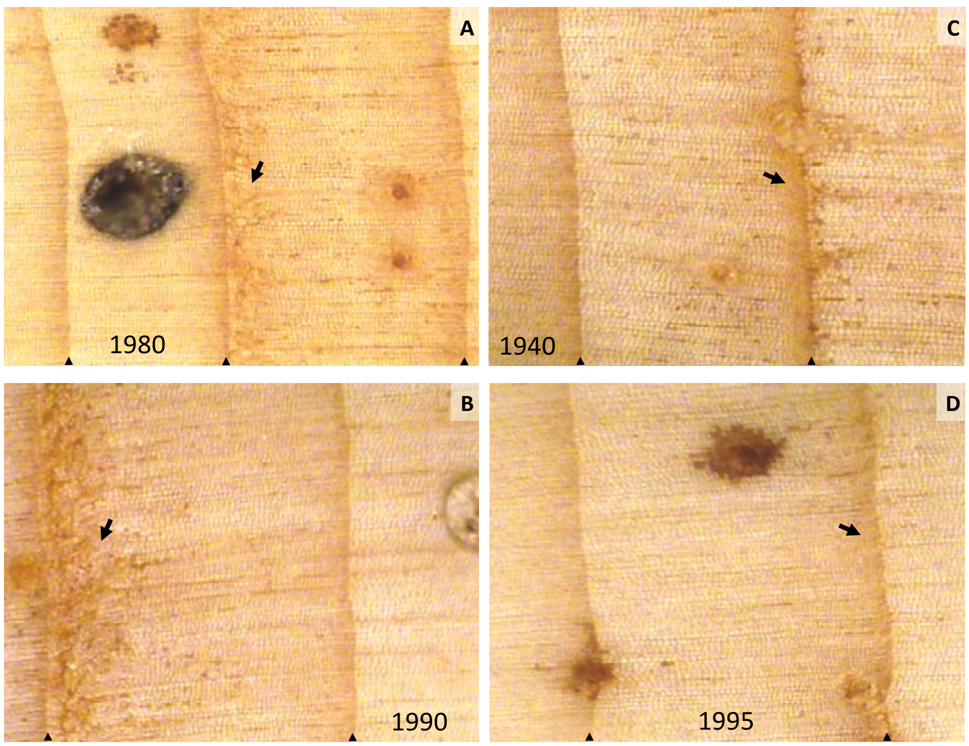

Figure 2 Four examples of frost injured tree-rings in earlywood and latewood of bristlecone pine from this study are indicated with arrows. Earlywood frost injured cells for years 1981 (A) and 1989 (B) show clear layers of collapsed amorphous tracheids cells with thin cell walls and discolored cell contents. The years of 1941 (C) and 1995 (D) show latewood frost anatomical features that include irregular layers of deformed, underlignified tracheids cells, and rays that are offset at the line of injury. Pictures taken at 30X (A) and 40X (B-D). The dark circle in 1980 (A) is a needle mark, and other dark dots are resin canals

The frequency of frost injury in any given year was tested for significance using the binomial distribution test (Equation 1) adopted from

Stahle (1990) to attach confidence intervals (CI) to the observed frequency of frost injured rings out of the total available sample of dated rings for each year (using $P < 0.05$):

$$CI = 1 \pm \left(\sqrt{\frac{p \times (1 - p)}{n}} \right) \times 2 \qquad (1)$$

Where p is the proportion of dated trees with frost injury in any given year, and n is the total number of trees dated to that year (STAHLE, 1990). The background frequency of frost-rings was calculated as the simple ratio of all frost-rings to the total number of dated rings. This way, frost-ring occurrence would be entirely random. To be significant, *p-CI* must exceed the random background frequency of frost-ring occurrence.

Climatic data were obtained from the Niwot Ridge Meteorological station D-1, which is located only 45 km north of Goliath Peak at an elevation similar to the study site (i.e., station D-1 is at 3739 m, the Goliath Peak bristlecone pine stand is at a 3400- 3600 m range, Figure1). Daily minimum and maximum temperature data are available for D-1 station from 1952 to 2008 and were examined to identify the exact day during the early growing season when the freeze events responsible for frost-ring formation probably occurred. In most cases the timing of the unusual freeze event was obvious and unambiguous.

The daily minimum and maximum temperature data were separated into two groups of frost-ring years and non-frost years (remaining years with no frost event). Time series of daily temperature were centered to the probable date of the frost-ring event and were then subjected to statistical analyses to determine the magnitude of the daily temperature anomalies associated with each tree-ring dated freeze event. T-tests were used to estimate the significance of the differences between the means of frost and non-frost years for predetermined periods before and after each hard freeze. Meteorological data of surface and upper air were obtained from the NCEP/NCAR Reanalysis Project (KALNAY et al., 1996) that provides data from 1948 to present. Synoptic maps were then plotted using Integrated Data Viewer from Unidata/UCAR (MURRAY et al., 2002).

4 RESULTS AND DISCUSSION

The results obtained in this study are discussed in the following sections.

4.1 Frost Injury in bristlecone pine at Goliath Peak, Colorado

The derived frost-ring chronology is based on 82 exactly dated cores from 51 trees at Goliath site, and extends from A.D. 1930 to 2010. Millennium-old bristlecone pines are present at Goliath Peak, but this study has focused on young frost-sensitive trees in order to derive an unbiased frost-ring chronology suitable for comparison with meteorological data. Dating accuracy was confirmed by comparison with the 1000-year long Goliath Peak bristlecone pine chronology independently developed by Graybill and Idso (1993). Additional dating confirmation was demonstrated for a subsample of 28 cores from 15 trees.

Frost-rings varied from one event to another in the severity of cell damage and their frequency of occurrence (see Figure 3 and APPENDIX A). General background frequency of frost injured rings (i.e., ratio of all frost-rings to the total number of dated rings) was 8.8%. This expressive proportion indicates that the study site is highly sensitive to freezing events. Earlywood frost-rings alone presented a 6.7% background frequency compared with a 2.2% for latewood frost-rings. The reason for a pronounced record of earlywood frosts could be related to the persistence of colder temperatures after winter and air drainage ways favored by the site’s topography. Here, the general random frequency (8.8%) was used to rigorously test for significance for all years with early and latewood frost-rings (Figure 3, APPENDIX A).

A total of 14 years from 1930 to 2010 presented frost-rings in significant fraction of the dated cores (Figure 3 and Table 1). The fraction of cores exhibiting frost injury ranged from 16 to 73% for the earlywood events, and from 11 to 65% for the latewood events. Ten of the 14 dated frost-rings were restricted to the springwood portion of the growth rings and reflect late-season freeze events during the beginning of the growing season (i.e., 1939, 1946, 1954, 1969, 1974, 1976, 1981, 1985, 1989 and 2001). Four frost-ring events were restricted to the latewood and reflect early-season freezes during August or September (i.e., 1941, 1961, 1965 and 1995). The three latewood frost-rings of 1941, 1961 and 1965, were previously identified by La Marche and Hirschboeck (1984) and Brunstein (1996).

Some years with at least one recorded frost-ring but with very low observed frequency are listed in Table 1 (bottom row). These non-significant frost-years could be due to insufficient sampling, or intrinsic factors (e.g., one or very few trees initiated radial growth favored by microsite conditions before the late-season freeze event, while most trees were still dormant).

Brunstein (1996) also reports the 1965 latewood frost-ring in Rocky Mountain bristlecone pines growing on the Almagre Mountain (3340 - 3700 m.a.s.l.) in the southern Front Range, Colorado. The 1965 frost damage was found in the latewood of five trees in a total of 47 sampled trees with the 1965 annual ring (11% of relative frequency). The relative low frequency of the 1965 frost-ring in Goliath Peak could be related to local meteorological conditions at that year, or might indicate that most trees had already ceased cambial activity at Goliath Peak (about 70 miles northwest from the Almagre Mountain).

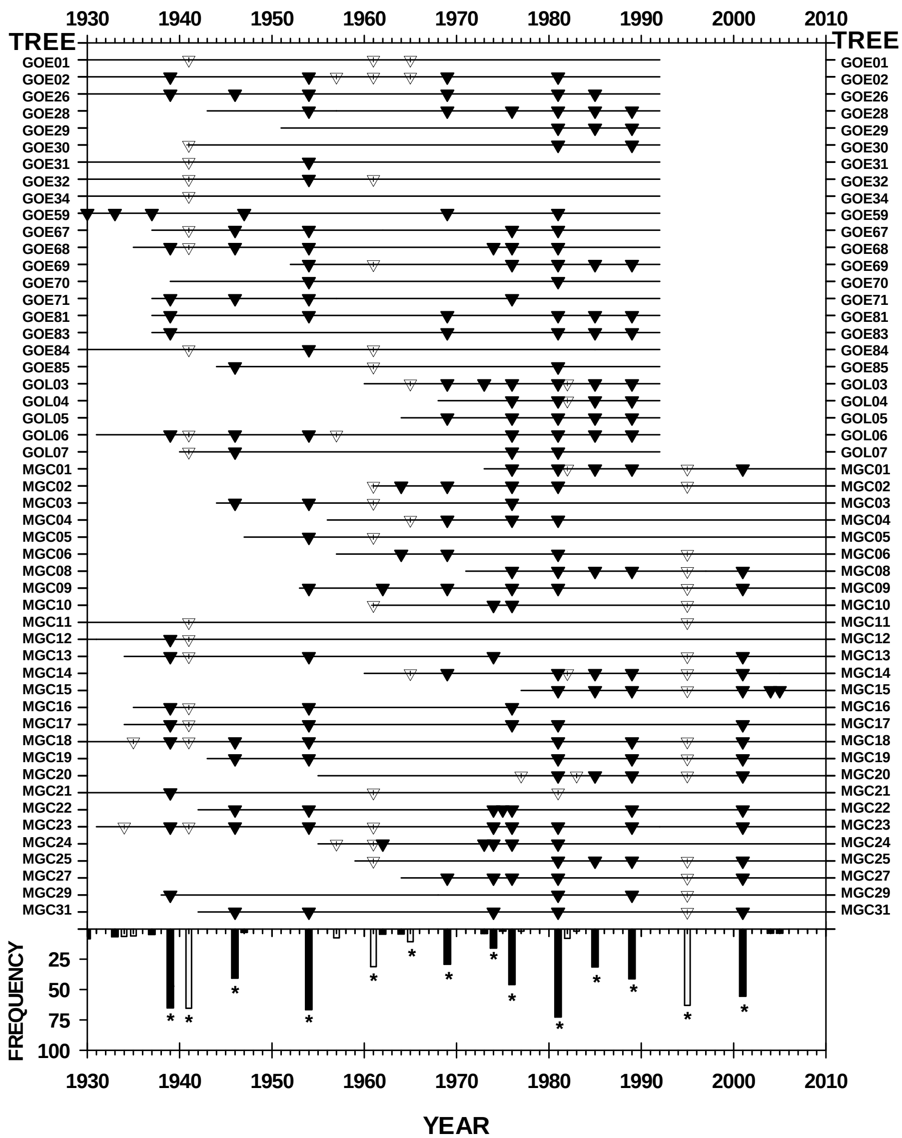

Figure 3 The frost-ring chronologies based on bristlecone pine samples from 51 trees at Goliath Peak study site are illustrated from 1930 to 2010. Years with evidence for frost injury are identified for each tree chronology by an inverted triangle and are discriminated into earlywood frost (black filled) and latewood frosts (light filled). The first collection from 1992 is listed at the top of the chart, followed by the second collection in 2010. A relative frequency plot is displayed on the bottom (%, Y axis reversed) and indicates major events for earlywood and latewood frosts (see Table 1 and APPENDIX A). * years significantly above the random frequency

The absence of frost injury in some sample trees during years with a significant frequency of frost damage is believed to reflect microsite differences which affect the intensity and duration of subfreezing temperatures, and physiological differences among individual trees which may affect the early initiation or termination of radial growth during the growing season. Younger trees growing near or in cold air drainage ways appear to record the largest number of earlywood frost-rings. The sample of dated trees is not large enough to test these suspected ecological associations of frost-ring formation, but southern exposures would certainly favor the early initiation of tree growth during warm springs and trees located on terrain subject to cold air drainage might as well experience the most intense subfreezing temperatures during late-season cold waves.

Table 1 List of years with early and latewood frost injury included in the frost-ring chronology (top row), with significant frequency, and other possible years of hard freeze (bottom row), see also APPENDIX A

	Earlywood frost injury	Latewood frost injury
Chronology	1939, 1946, 1954, 1969, 1974, 1976 1981, 1985, 1989, 2001	1941, 1961, 1965, 1995
Other years	1930, 1933, 1937, 1964, 1973, 1975, 2004, 2005	1934, 1935, 1957, 1977, 1982, 1983

4.2 Daily temperature analysis

The daily mean temperatures from 1952 to 2008 are presented in Figure 4. The daily temperature data for station D-1 were carefully examined during the growing seasons of 1954, 1961, 1965, 1969, 1974, 1976, 1981, 1985, 1989, 1995, and 2001 in order to identify the exact timing of the severe subfreezing weather responsible for frost damage to the Goliath Peak bristlecone pine during these particular years.

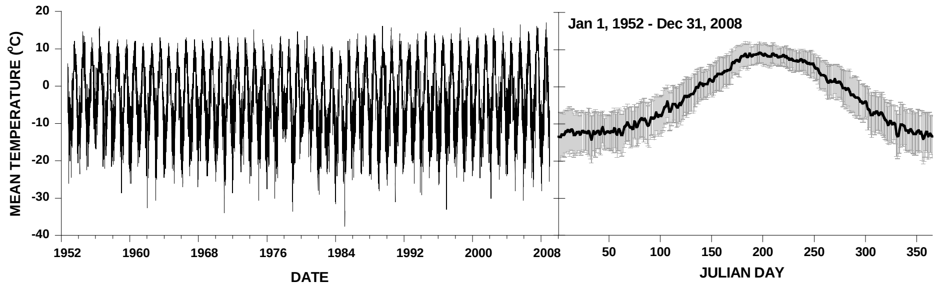

Figure 4 Daily mean temperature from Niwot Ridge station D-1 for consecutive years from January 1, 1952 to December 31, 2008 (left), and average daily mean temperature in Julian days (right), gray bars indicate one standard deviation

A careful examination of the climate records from June to September was conducted to check for anomalous low temperature outbreaks from 1952 to 2008. Other years with freezing events that could potentially cause frost damage to growing trees were found. However no frost-ring record for those years was observed in the sampled cores from Goliath Peak, which may have a different microclimatology from Niwot Ridge. Most of these freezing climate records with no observed frost damage in trees happened in early June and late September and perhaps during those years most trees were dormant. Dry years could also delay or shorten growth period of the trees, thus preventing frost injury.

The daily minimum and maximum temperature data for Niwot Ridge are plotted in Figure 5 from April 1 to July 31 for the eight earlywood frost events (1954, 1969, 1974, 1976, 1981, 1985, 1989, and 2001), and in Figure 6 from July 1 to October 31 for the three latewood frost events (1961, 1965 and 1995). In all cases, minimum temperatures fell below -5°C during the probable growing season freezes associated with these eleven frost-ring events. Previous empirical and experimental research has demonstrated that temperatures below -5°C during the period of active growth are sufficient to induce traumatic freeze damage in trees, including the unique anatomical damage which is characteristic of frost-injured growth rings (GLERUM; FARRAR, 1966; GLOCK; REED, 1940; STAHLE, 1990).

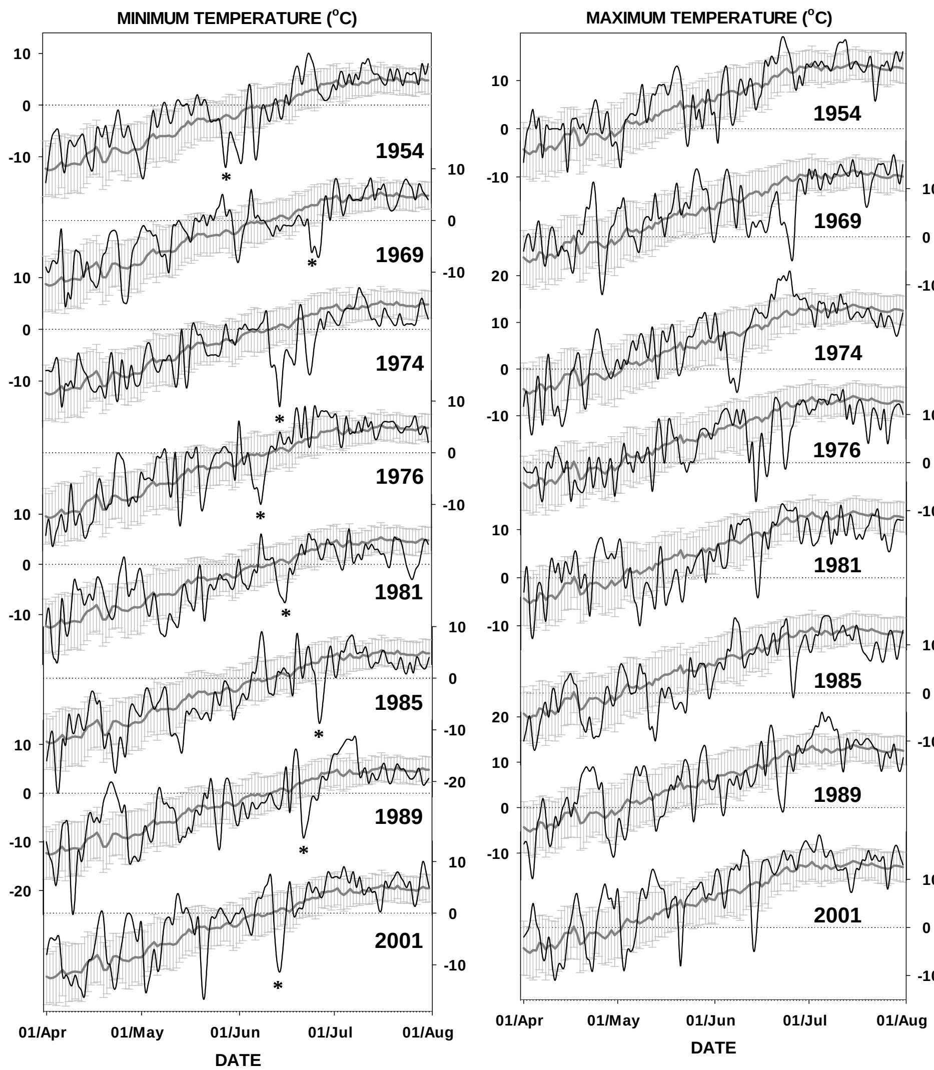

Figure 5 The daily minimum (left) and maximum (right) temperature data for Niwot Ridge station D-1 from April 1 to July 31 for the eight years with earlywood frost events (1954, 1969, 1974, 1976, 1981, 1985, 1989, and 2001). The gray line is the average daily minimum and maximum temperatures computed from the 46 remaining years with no frost events between 1952 and 2008. The gray bars indicate one standard deviation from mean for the non-frost years

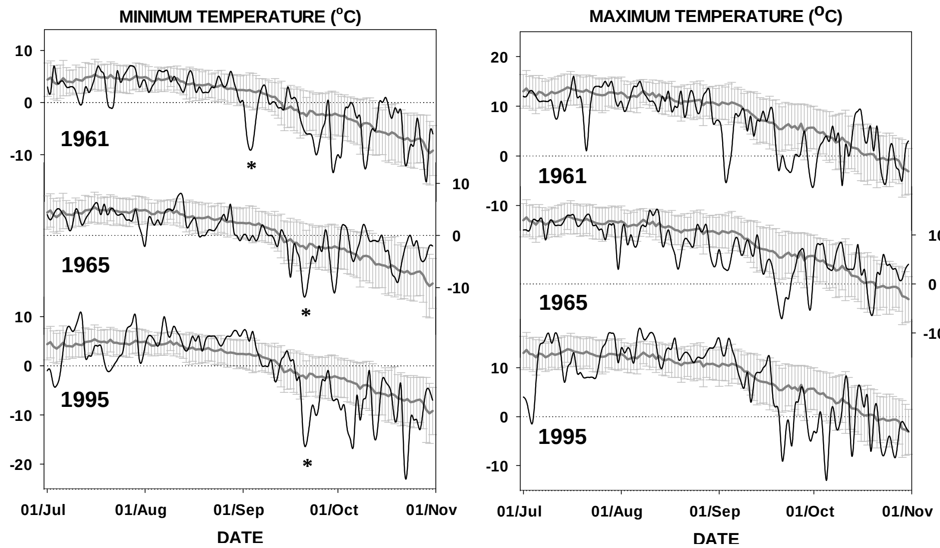

Figure 6 The daily minimum (left) and maximum (right) temperatures data for Niwot Ridge station D-1 from July 1 to October 31 for the three years with a significant frequency of latewood frost damage. The gray line is the average daily minimum and maximum temperatures computed from the 46 remaining years with no frost events between 1952 and 2008. The gray bars indicate one standard deviation from mean of the non-frost years. Note the amazing freeze event on July 4th, 1995 on Niwot Ridge which was probably not quite cold enough to induce frost-ring damage at Goliath Peak

The year of 1954 was the only one when freezing temperatures occurred before mid to late-June (Figure 5), and experienced three consecutive low temperature episodes: May 28 (-12°C), June 02 (-11°C), and June 6 (-9°C). May 28 was considered to be the day of the event in 1954 for two reasons: 1) the presence of a warm spell during the days prior to freezing temperatures, and 2) it was the coldest day registered during a week-long cold wave. The timing of the other freeze events was much less ambiguous. Latewood frost events (Figure 6), as expected, took place late in the growing season during the month of September and might have induced cambial dormancy (GLERUM; FARRAR, 1966).

In order to examine the common phenomena involved in the formation of late and early-season frosts in Goliath peak bristlecone pines, the date of the hard freeze (F) was used to center the daily temperature data (F = 0). Two approaches were then used to test if warm and cold phases regarding the ten frost events represent clear departures from the normal seasonal temperatures, following the methodology described by Stahle (1990): 1) two-tailed test between means of daily temperatures for multiple day time intervals before and after the freeze for the years with frost damage rings compared with the 46 remaining years with no frost-ring events (Tables 1 and 2), and 2) time series plots of mean daily temperatures for all frost and non-frost years with their respective confidence intervals (Figure 7).

Table 2 presents the t-test results for earlywood frost years performed for two different time periods. The periods tested were a three week interval starting 28 days to seven days prior to the freeze event (F), and a ten day period beginning one day before and ending eight days after freeze. Climatic warming was not significant for the period prior to hard freeze (F-28 to F-7), but the cold spell was significantly below normal during the cold phase of spring frost events. The lack of a prolonged warm period prior to the freeze indicates that the earlywood frosts at Goliath Peak do not represent classic false spring events (STAHLE, 1990) but instead represent highly unusual outbreaks of subfreezing temperatures early in the growing season.

The t-test for latewood frost years was also performed for two time periods and is presented in Table 3. The first time period analyzed was from June 15 to September 15 because it represents the growing season of bristlecone pines in Colorado Rockies (BRUNSTEIN, 1996), when the temperature records for mean minimum monthly temperatures are above freezing. The second period was again a ten day period beginning one day before and ending eight days after the event day. During the growing season, minimum, maximum, and mean temperatures were below normal (> 95% of confidence). The cold spell presented more intensely cold temperatures compared with non-frost years (> 99% of confidence).

Table 2 T-Tests comparing mean daily maximum (MAX), minimum (MIN), and mean temperatures (^{o}C) of frost (FY) and non-frost years (NFY) for a time period before and after the freeze event day (F). The degrees of freedom were 8004 and 3678 for the first and second period, respectively

PERIOD	FY	NFY	T-TEST	P
F-28 to F-7, MAX	5.6	5.7	-0.221	0.825
F-28 to F-7, MIN	-2.2	-2.1	-0.248	0.805
F-28 to F-7, MEAN	1.7	1.8	-0.244	0.807
F-1 to F+8, MAX	7.2	10.1	-4.98	< 0.001
F-1 to F+8, MIN	-2	1.6	-7.27	< 0.001
F-1 to F+8, MEAN	2.6	5.8	-6.26	< 0.001

Table 3 T-Test comparing mean daily maximum (MAX), minimum (MIN), and mean temperatures (^{o}C) of frost (FY) and non-frost years (NFY) after the latewood frost event (F). The degrees of freedom were 4463 and 1378 for the first and second period, respectively

PERIOD	FY	NFY	T-TEST	P
Jun 15 - Sep 15, MAX	10.3	11.6	-5.356	< 0.001
Jun 15 - Sep 15, MIN	2.8	3.4	-2.887	0.004
Jun 15 - Sep 15, MEAN	6.6	7.5	-4.403	< 0.001
F-1 to F+8, MAX	1.4	7.2	-6.430	< 0.001
F-1 to F+8, MIN	-5.0	-0.8	-5.282	< 0.001
F-1 to F+8, MEAN	-1.8	3.2	-6.129	< 0.001

These results are confirmed by the time series analysis plotted in Figure 7. In general, significant cold temperatures persisted for only a few days before and after the event day for the earlywood frost years and the cold anomaly was very extreme (Figure 7 A and B). However, the prevailing meteorological conditions prior to and during the formation of bristlecone pine frost-rings in the earlywood and latewood portions of the annual rings are quite different. For latewood frost-rings, La Marche and Hirschboeck (1984) and Brunstein (1996) describe below average summer temperatures prior to the early-season outbreak of subfreezing air in late August or September, and is consistent with the t-test results for mean temperature from June to September (Table 3). These cooler than average summer temperatures are believed to delay both the onset and termination of radial growth in high elevation bristlecone pine, rendering the still active cambium vulnerable to frost injury during early-season outbreaks of cold air in Autumn (LA MARCHE; HIRSCHBOECK, 1984). However, in Figure 6 and 7, temperatures were above average from 20 to 30 days before the freeze event which probably contributed to the continuation of the growth and the subsequent freeze damage.

A pattern of unusually warm late winter and early spring conditions followed by a late-season outbreak of intense subfreezing air is referred to as "false spring," and was associated with all 13 frost- ring events recorded by oak trees in the southcentral United States during the period of instrumental weather observation (STAHLE, 1990). These relatively warm temperatures prior to the late-season freeze events are believed to stimulate the onset of radial growth, breaking cambial dormancy during this preceding warm spell and leading trees to be vulnerable to freeze damage and frost-ring formation during the subsequent outbreak of cold, subfreezing air. Nevertheless, this evidence was not clearly confirmed by the results presented here for the bristlecone pines at Goliath Peak. It is true that cambial activity must have initiated prior to the impact of frost in order that the newly formed cambial derivatives could be affected (GLOCK, 1951), but the duration of warmer than average daily temperatures was very short for the eight earlywood frost events at Goliath Peak (i.e., F-3 to F-7, Figure 7). Therefore, the weather anomalies, associated with the earlywood frost damage at Goliath Peak might be more accurately described as an early growing season freeze event rather than false spring.

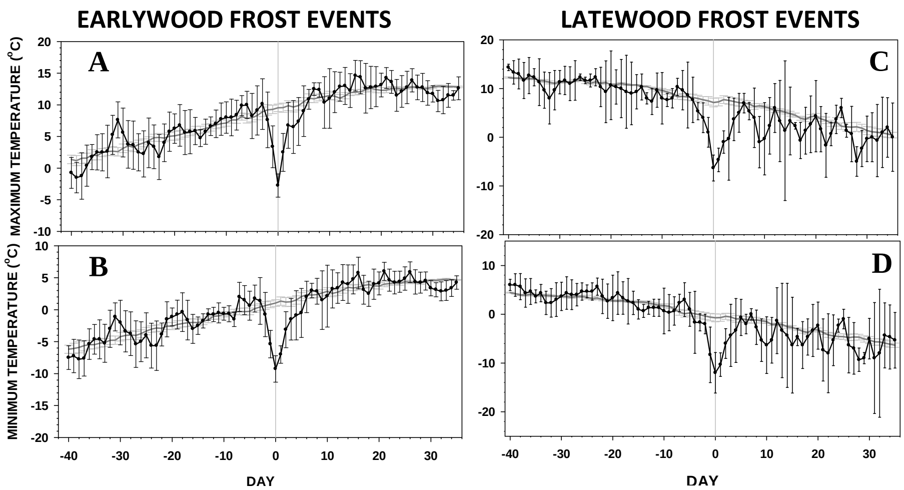

Figure 7 The composite daily average maximum (upper) and minimum (lower) temperature anomalies of eight earlywood frost (A and B), and three latewood frost (C and D) episodes are plotted for 40 days before and 35 days after the hazard freeze event (F = 0), along with the average daily temperatures computed from remaining non-frost years between 1952 and 2008. The confidence intervals represent the two standard errors associated with each daily average

Note that earlywood frost was not a prelude to colder mid growing season conditions (F+7 to F+30, Figure 7 A and B), but latewood frost was the beginning of at least a month colder than normal temperatures (F+1 to F+30, Figure 7 C and D), even though the sample only includes three events.

4.3 Synoptic meteorology of frost-rings in Goliath Peak bristlecone pine

The sequence of meteorological events associated with the late-season freeze is illustrated with selected surface temperature and the geopotential height field at the 500 mb level (Figure 8A-P). The general pattern of the average synoptic meteorological conditions during the two week interval prior to and during the freeze event documents the dramatic circulation changes over North America which attended the outbreak of cold air over the western United States. Upper air winds (not shown) and the height of the 500 mb pressure surface (Figures 8A, C, E, G, I, K, M and O) indicate mostly zonal flow over the northcentral United States which favored normal or above normal surface temperatures over central Colorado.

The surface temperature and the 500 mb maps indicate that the cold high pressure cell was advected into the Great Basin, and was associated with unseasonably cool temperatures across much of the western United States during the freeze event related with earlywood frost damage (Figure 8B, D, F, H, J, L, N and P). Deep meridional flow developed over western North America with the intensification and eastward migration of this flow. The upper level trough was located near Colorado, and this circulation pattern resulted in the advection of the cold surface high pressure cell into the western United States (Figure 8).

The development of a deep trough in the upper level circulation over the western United States, and the advection of a cold surface high pressure cell into the central Rocky Mountains occurred in all eight earlywood frost-ring events analyzed since 1952. Freezing temperatures for 12:00Z (0:00 UTC time zone) from the NCEP/NCAR Reanalysis Project data (KALNAY et al., 1996) used to compile the surface maps for the United States may underestimate the elevation gradient, but subfreezing temperatures would have been more widespread at high elevation sites across the West, including the minimum temperatures of -7 to -15°C recorded at station D-1 on Niwot Ridge for each late-season frost event.

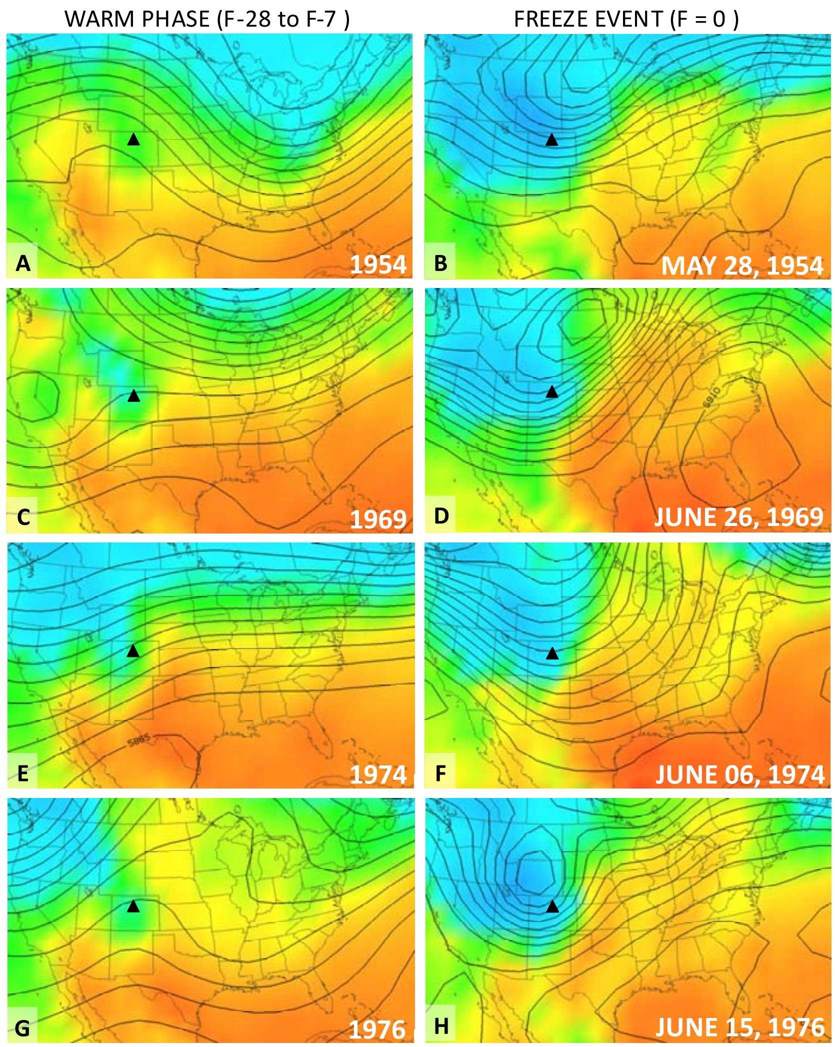

Figure 8 Synoptic weather maps for 1954, 1969, 1974, 1976, 1981, 1985, 1989, and 2001, illustrating the warm (left maps) and cold (right maps) phases of earlywood frosts events. The black contour indicates the geopotential height at 500 mb level with a 30 m increment. The colors indicate surface temperatures (daily means for the warm phase, and daily 12:00Z single temperature for the freeze events). The data come from the NCEP/NCAR reanalysis project (KALNAY et al., 1996) (…continue…)

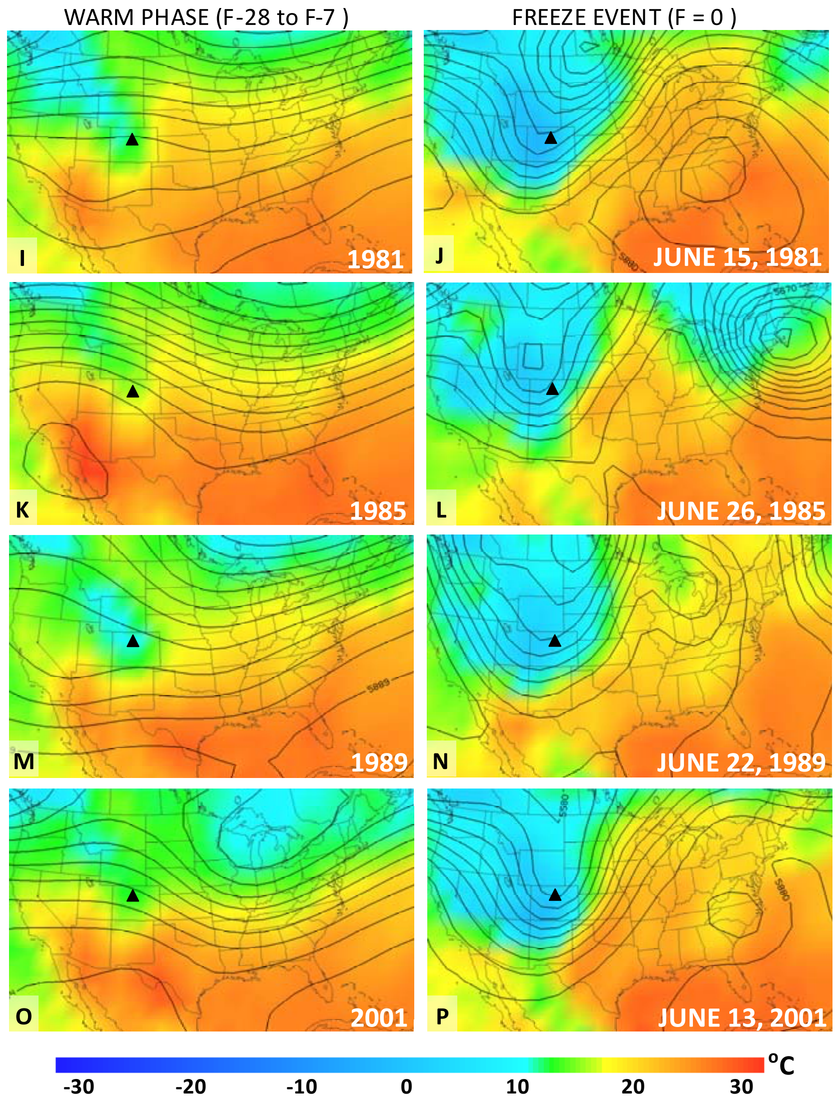

Figure 8 Synoptic weather maps for 1954, 1969, 1974, 1976, 1981, 1985, 1989, and 2001, illustrating the warm (left maps) and cold (right maps) phases of earlywood frosts events. The black contour indicates the geopotential height at 500 mb level with a 30 m increment. The colors indicate surface temperatures (daily means for the warm phase, and daily 12:00Z single temperature for the freeze events). The data come from the NCEP/NCAR reanalysis project (KALNAY et al., 1996)

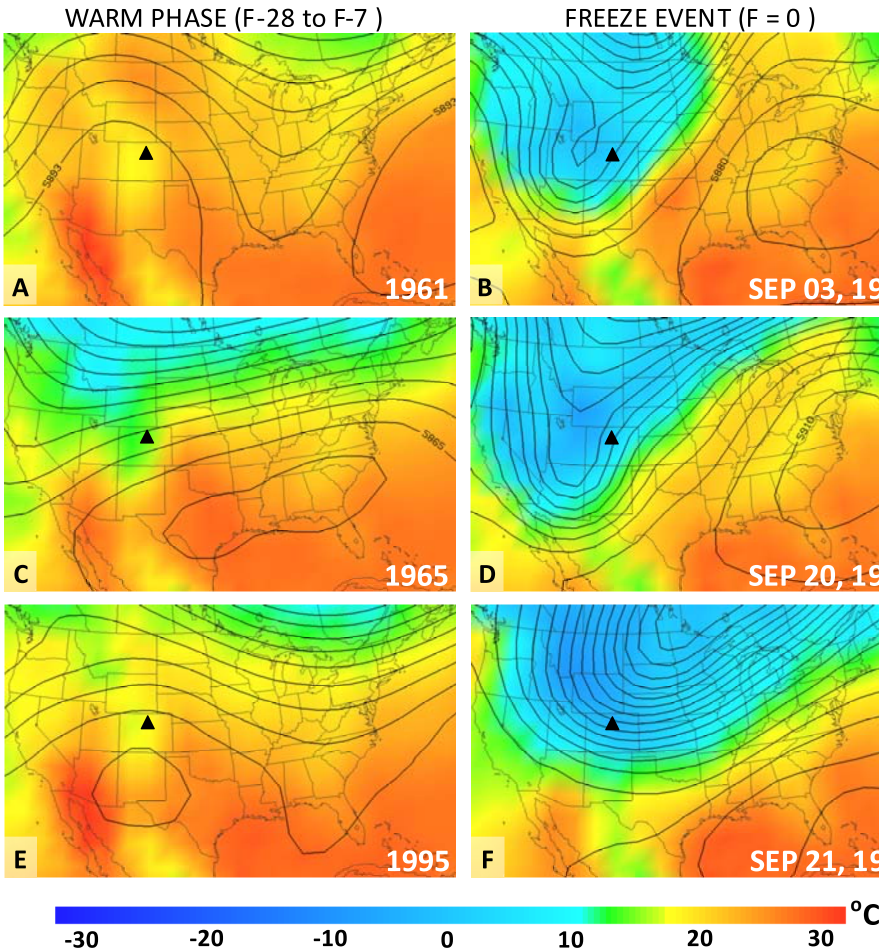

Figure 9 Synoptic weather maps for 1961, 1965, and 1995, illustrating surface temperature and 500 mb height for the warm (left maps) and cold (right maps) phases involved in latewood frost events during respective years. The black contour indicates the geopotential height at 500 mb level with a 30 m increment. Colors represent surface temperatures means (A, C, and E), and single temperature at 12:00Z (B, D, and F). The data come from the NCEP/NCAR reanalysis project (KALNAY et al., 1996)

The meteorological events related with the early-season freeze are also illustrated with surface and upper air data (Figure 9A-F). In early to mid-September in each of these latewood frost events, a severe outbreak of unseasonably cold air from higher latitudes probably caused these latewood frost-rings. The Niwot Ridge station recorded minimum daily temperatures of -9^{o}C on September 03, 1961, -11 ^{o}C on September 20, and -16^{o}C on September 21, 1995. In all years the duration of the late-summer freezing temperatures lasted for more than three days.

5 SUMMARY AND CONCLUSIONS

The key findings of this research are:

(1) Frost-rings occurred with an expressive high frequency at Goliath Peak, Colorado, which is strong evidence that this site is one of the most frost-sensitive location ever registered. Sites with similar conditions, with trees growing near or in cold air drainage ways, verified by suppressed treeline, are indeed potential for studies of this kind.

(2) Earlywood frost-rings were far more common than latewood frosts at Goliath Peak and did not seem to be related with false-springs, but instead represented highly unusual late-season outbreaks of severe subfreezing temperatures early in the growing season.

(3) Below average summer temperatures were related with latewood frosts and are believed to delay the onset and termination of radial growth in high elevation bristlecone pine, rendering the trees vulnerable to frost injury during early-season outbreaks of cold air.

(4) Frost-rings in bristlecone pine can be dated to the exact year of occurrence with dendrochronology and available daily temperature records can enable further investigation at daily timescales. In most cases, Earlywood frosts were found to take place on mid to late June, while latewood frosts occurred during the month of September.

(5) In all cases for which synoptic meteorological data were available, early and latewood frost damage to bristlecone pine on Goliath Peak occurred

following the large-scale advection of cold air masses. These dendrometeorological inferences can be drawn only when indicated by the widespread occurrence of synchronous frost-rings, but are far more detailed than dendroclimatic reconstructions which are routinely derived from total ring width or density chronologies and tend to reflect the average climatological conditions prior to and during the growing season.

6 STUDY LIMITATION AND RECOMMENDATIONS

Sampling was the main limitation of this research, and it is possible that the trees indeed record every single freeze event in sensitive sites located at high elevation mountains of the Rockies. Further studies should consider multi-site sampling and mapping the frequency of frost-rings occurrence in bristlecone pines, together with a careful analysis of physiological traits of the growing season based on soil moisture, radiation, and temperature forcing.

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APPENDIX

APPENDIX A – Table of frost-rings frequency

Frost-rings in sampled bristlecone pines at Goliath Peak, Colorado. NFR: number of dated trees with earlywood (EW) or latewood (LW) frost injury in any given year; N: total number of trees dated to each given year; P: proportion of dated trees with frost-ring; CI: the 95% confidence interval around the proportion of frost-rings calculated using the binomial distribution; *: significant years, that is, CI exceeded the random background frequency of frost year occurrence. The background frequency (8.84%) was calculated as the simple ratio of all frost-rings (261) to the total number of dated rings (2952).

Year	NFR		N	P (%)	CI	
1930	1	EW	12	8.33	8.22	8.44
1931			14			
1932			14			
1933	1	EW	15	6.67	6.57	6.77
1934	1	LW	16	6.25	6.15	6.35
1935	1	LW	17	5.88	5.79	5.98
1936			17			
1937	1	EW	21	4.76	4.68	4.85
1938			22			
1939*	15	EW	23	65.22	65.03	65.41
1940			24			
1941*	17	LW	26	65.38	65.19	65.57
1942			29			
1943			30			
1944			32			
1945			32			
1946*	13	EW	32	40.63	40.43	40.82
1947	1	EW	33	3.03	2.96	3.10
1948			33			
1949			33			
1950			33			
1951			34			

(…continue…)

(…continuation…)

Year	NFR		N	P (%)	CI	
1952			35			
1953			36			
1954*	24	EW	36	66.67	66.48	66.86
1955			38			
1956			39			
1957	3	LW	40	7.50	7.39	7.61
1958			40			
1959			41			
1960			43			
1961*	14	LW	45	31.11	30.93	31.30
1962			45	4.44	4.36	4.53
1963			45			
1964	2	EW	47	4.26	4.17	4.34
1965*	5	LW	47	10.64	10.51	10.76
1966			47			
1967			47			
1968			48			
1969*	14	EW	48	29.17	28.98	29.35
1970			48			
1971			49			
1972			49			
1973	2	EW	50	4.00	3.92	4.08
1974*	8	EW	50	16.00	15.85	16.15
1975	1	EW	50	2.00	1.94	2.06
1976*	23	EW	50	46.00	45.80	46.20
1977	1	LW	51	1.96	1.91	2.02
1978			51			
1979			51			
1980			51			
1981*	37	EW	51	72.55	72.37	72.73
1982	4	LW	51	7.84	7.74	7.95
1983	1	LW	51	1.96	1.91	2.02

(…continue…)

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Year	NFR		N	P (%)	CI	
1984			51			
1985*	16	EW	51	31.37	31.19	31.56
1986			51			
1987			51			
1988			51			
1989*	21	EW	51	41.18	40.98	41.37
1990			51			
1991			51			
1992			51			
1993			27			
1994			27			
1995*	17	LW	27	62.96	62.77	63.16
1996			27			
1997			27			
1998			27			
1999			27			
2000			27			
2001*	15	EW	27	55.56	55.36	55.75
2002			27			
2003			27			
2004	1	EW	27	3.70	3.63	3.78
2005	1	EW	27	3.70	3.63	3.78
2006			26			
2007			26			
2008			26			
2009			26			
2010			26			

ARTICLE 2: A spatial and temporal analysis of tree growth and climate in the southcentral United States

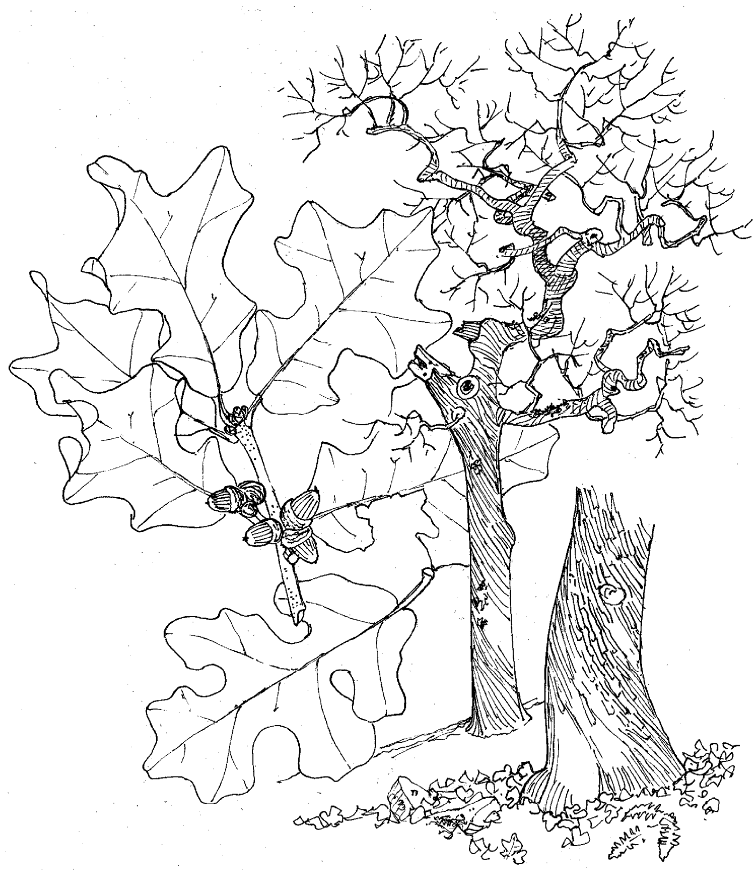

Illustration by **Fred Paillet**, Geosciences Department, University of Arkansas

ABSTRACT

A dendroclimatic study was conducted to evaluate how climate affects radial growth patterns across an environmental gradient that parallels the vegetation continuum in the southcentral United States. Tree-ring chronologies derived from post oak (*Quercus stellata*) were selected from 55 sites scattered from southern Texas to central Missouri, comprising three major ecosystems: Ozark oak-hickory forest, Cross Timbers, and Post-oak Savanna. Palmer Drought Severity Index (PDSI) and Palmer Moisture Anomaly Index Z were obtained for each site from a 0.5^{o} gridded database. Four data sets were prepared to analyze spatial and temporal patterns of tree growth, and the potential growth influences of climatic and non-climatic factors using principal components analysis (PCA) and rotated PCA: (1) 55 tree-ring chronologies (pre-whitened residuals), (2) Palmer Z-indices for the 44 grid points closest to each of the 55 tree-ring sites, (3) "signal free" tree-ring chronologies (residuals from regression with the June PDSI), and (4) tree-ring chronologies (same as number 1 for non-overlapping 50-yr sub-periods from 1751-1950). The results of comparisons between moisture anomalies and tree growth indicate that the spatial patterns of tree growth largely conform with the spatial patterns of climate, as measured by the Z-index for June. Yet, a considerable amount of residual variance was left over after removing the climate signal from tree-ring records and indicates possible phenology and disturbance driven spatial patterns of tree growth. Temporal analysis conducted for 50-yr sub-periods over a 200-yr indicated that the spatial patterns for the first two PCs of tree growth exhibited only modest changes over time.

Keywords: Dendroecology. Post oak. *Quercus stellata.*

RESUMO

Um estudo dendroclimatológico foi realizado com *Quercus stellata* para avaliar a influência do clima nos padrões de crescimento radial de árvores, ao longo de um gradiente ambiental que é paralelo ao da vegetação, no centro-sul dos Estados Unidos. Foram utilizados registros de 55 sítios distribuídos aleatoriamente do sul do estado do Texas ao centro do estado de Missouri, abrangendo três ecossistemas: *Ozark oak-hickory forest*, *Cross Timbers* e *Post-oak Savanna*. O índice de severidade de seca de Palmer (PDSI) e o índice Z de anomalia de umidade de Palmer foram obtidos para cada sítio a partir de uma base de dados com resolução espacial de 0,5°. Foi realizada análise de componentes principais (PCA) e de PCA rotacionada (RPCA) em quatro bases de dados, para a avaliação espacial e temporal dos padrões de crescimento das árvores e do potencial de influência de fatores climáticos e não climáticos: (1) 55 cronologias de anéis de crescimento (resíduos), (2) índice Z de Palmer para 44 pontos de grade correspondentes aos 55 sítios de registro de anéis de crescimento, (3) registros de crescimento sem sinal climático (resíduos da regressão com o índice de severidade de Seca de Palmer - PDSI - de junho), e (4) cronologias de anéis de crescimento sem sobreposição, em períodos de 50 anos, de 1751 a 1950. Em geral, o padrão de crescimento radial das árvores foi semelhante aos padrões dos índices de umidade de junho. Após a remoção do sinal de umidade de junho, a distribuição espacial da variância foi provavelmente relacionada à fenologia (sazonalidade da quebra de dormência de *Quercus stellata*) e com a ocorrência de distúrbios (como tornados, queimadas e granizo). A análise dos períodos de 50 anos indicou que o padrão espacial de crescimento das árvores foi estável ao longo do tempo.

Palavras-chave: Dendroecologia. Post oak. *Quercus stellata*.

1 INTRODUCTION

The Cross Timbers are a complex mosaic of upland deciduous forest, savanna, and glade communities from a broad ecotone between the eastern hardwood forests of the Ozarks Plateau and Ouachita Mountains, and the grasslands of the southern Great Plains (BRUNER, 1931; DYKSTERHUIS, 1948; KUCHLER, 1964). A similar transition zone, known as the Post Oak Savannas, occurs in the southernmost extension of the oak forests and separates the eastern Pinewoods from the prairies in central Texas (RIDEOUT, 1994). The east-to-west vegetation continuum in the southcentral United States parallels the decline in annual precipitation as eastern deciduous forests (oak-hickory and oak-pine dominated communities) gradually shift into grassland ecosystems of the Great Plains. Extensive quantitative evidence has been reported by Rice and Penfound (1959) indicating that the species diversity, arboreal dominance, and basal area of upland forest of Oklahoma decrease from relatively mesic forests in the eastern part of the state to more xeric stands in the west along the margin of the Southern Plains. Similar changes are known to occur north and westward from the forest portions of northeastern Kansas and elsewhere along the eastern fringe of the Great Plains.

Predictive models together with field observations and increment cores validation studies have identified many large tracts of ancient post oak woodlands noncommercial for timber spread from southern Texas to Missouri (BAYARD, 2003; PEPPERS, 2004; STAHLE; CHANEY, 1994; THERRELL, 1996; THERREL; STAHLE, 1998). These old growth remnants provide an excellent opportunity to study the environmental factors important in post oak growth and distribution, offering a unique quantitative means to extend short term observations into the past 200 to 400 years (FRITTS, 1976).

Post oak (*Quercus stellata* Wangenh.) is found from the Atlantic coast to central Texas, and is often dominant or existing as a minor component of the Cross Timbers, oak-hickory, oak-pine, cedar glade, and southern mixed-forest vegetation types in the southcentral United States (KUCHLER, 1964). The species is well suited for dendrochronology because it produces well-defined annual growth rings, is long lived, and is often slow growing (HARPER, 1961; JOHNSON; RISSER, 1973; STAHLE; HEHR, 1984).

A number of previous studies have examined tree-rings from post oak trees and their correlation with climate (CLARK, 2003; HARPER, 1961; JOHNSON; RISSER, 1973; PEPPERS, 2004; STAHLE; HEHR, 1984; STAHLE et al., 1985). Dendroclimatic research in the southcentral U.S. has indicated that tree growth is affected by the precipitation gradient, and post oak chronologies tend to become more variable and climate sensitive westward toward the prairie border, consistent with the decline in rainfall (STAHLE; HEHR, 1984). Cook et al. (2001) conducted a dendroclimatic study with different tree species in the Big Thicket region to evaluate how climate affects the radial growth of native species across the precipitation gradient. Rotated PCA revealed phylogenetic association among species that appeared to be more important than ecological characteristics of the collection sites in determining the growth and climate relationships among species (COOK et al., 2001).

In this work we eliminate phylogeny and consider the spatial and temporal behavior of tree growth for only one species to address the following hypotheses: (1) the most important tree growth patterns of post oak in the southcentral United States can be explained by climate, (2) these growth patterns are stable over time, and (3) the residual patterns of post oak growth, after removing the influence of climate, reflect regional gradients in phenology, disturbance, or soil characteristics. To address these questions a network of 55 post oak chronologies and 44 co-located growing season climate records are compared using PCA and RPCA.

2 MATERIAL AND METHODS

Detailed descriptions of the study area and methodology are described in the following sections below.

2.1 Tree-ring network and study area

The post oak ring-width data were obtained from two databases: the University of Arkansas (Fayetteville) Tree-Ring Laboratory, and the International Tree-Ring Data Bank (2010), maintained by the NOAA Paleoclimatology Program and World Data Center for Paleoclimatology. The raw ring-widths chronologies selected were developed from 55 different sites (Figure 1 and Table 1) scattered from 28.7^o to 38.4^o N and from 90.2^o to 99.2^o W, throughout the vegetation continuum zone comprising three major ecosystems: Ozark oak-hickory forest, Cross Timbers, and Post oak Savanna (KUCHLER, 1964).

All tree-ring data were developed using standard dendrochronological procedures (FRITTS, 1976; STOKES; SMILEY, 1968) for drying, mounting, sanding the increment cores, using crossdating to assign calendar years to the annual rings, and measuring the ring widths. For each tree-ring collection per site, the individual ring width series were checked for crossdating and overall quality using the program COFECHA (HOLMES, 1983). Table 1 presents the respective reference for each collection site.

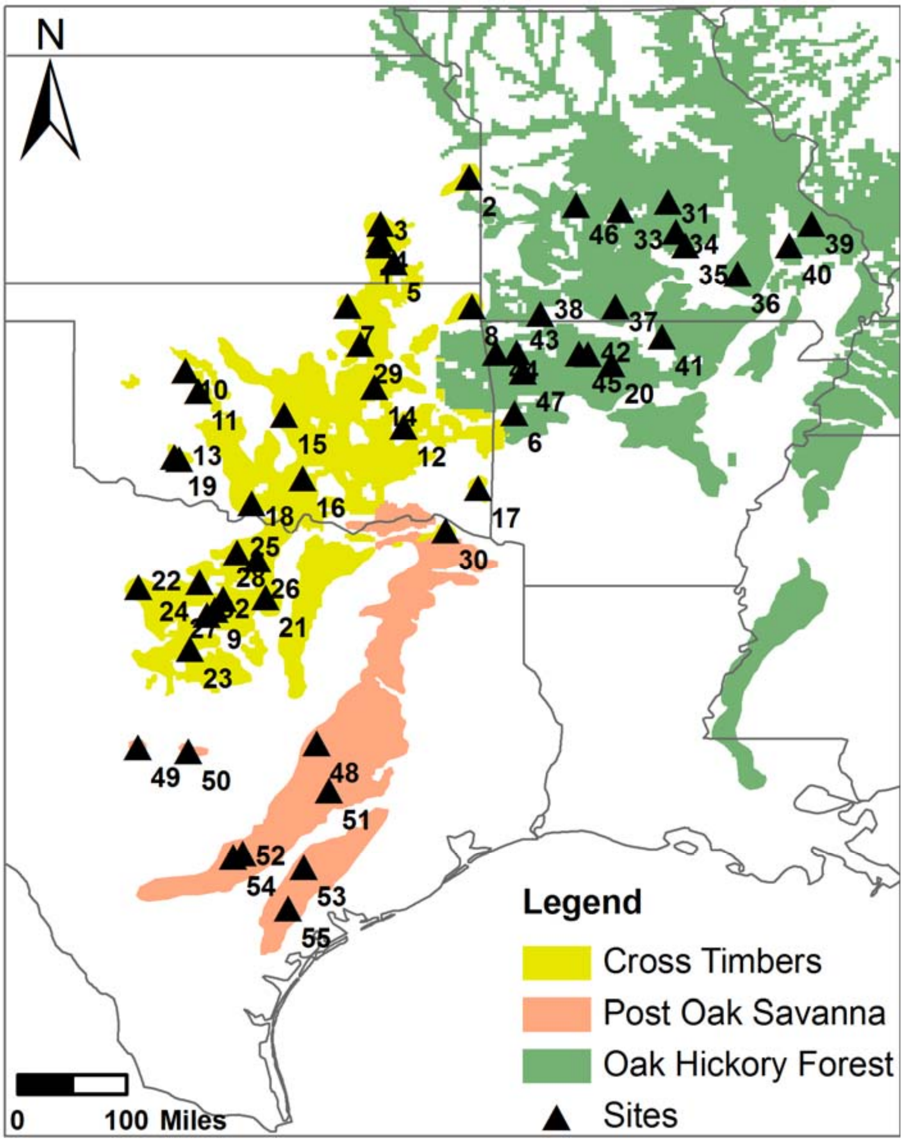

Figure 1 Map indicating the location of the sites (numbers correspond to Table 1) in the Oak Hickory Forest, Cross Timbers and Post Oak Savanna ecosystems (KUCHLER, 1964)

Table 1 Summary of the 55 sites with post-oak chronologies.

	Ecosystem	Site Name, State*	Lat	Long	Alt (m asl)	Soil	Interval	Ref.
1	**Cross**	Lazy S - B Ranch, KS[1]	37.50	-95.97	307	Sandstone	1758-2006	*a*
2	**Timbers**	McClosky Ranch, KS	38.40	-94.77	260	Shale	1714-1982	*b*
3		Toronto Lake, KS[1]	37.78	-95.95	290	Sandstone	1728-1982	*b*
4		Fall River, KS[1]	37.58	-95.95	285	Sandstone	1738-1982	*b*
5		Elk River, KS	37.28	-95.78	290	Limestone	1724-1982	*b*
6		Christmas Knob, AR	35.29	-94.16	160	Sandstone	1788-2008	*c*
7		Blue Stem Lake, OK	36.70	-96.39	260	Sandstone	1737-1982	*b*
8		Neosho River, OK	36.70	-94.73	275	Limestone	1675-1982	*b*
9		Keystone Lake, OK	36.20	-96.22	275	Sandstone	1611-1995	*b*
10		Oakwood, OK	35.85	-98.55	500	Sandstone	1772-1980	*b*
11		Canadian River, OK	35.58	-98.38	455	Sandstone	1680-1982	*b*
12		Lake Eufala, OK	35.11	-95.64	210	Sandstone	1745-1980	*b*
13		Quanah Mountain, OK[2]	34.69	-98.64	425	Granite	1686-1980	*b*
14		Okmulgee, OK	35.63	-96.03	235	Sandstone	1691-2008	*d*
15		Hog Creek, OK	35.27	-97.23	355	Sandstone	1753-1982	*c*
16		Lake Arbuckle, OK[3]	34.43	-96.99	280	Conglomerate	1698-1995	*b*
17		McCurtain County, OK[3]	34.30	-94.65	260	Sandstone	1685-1982	*b*
18		Mud Creek, OK	34.10	-97.67	260	Sandstone	1691-1995	*b*
19		French Lake, OK[2]	34.72	-98.70	494	Granite	1713-2005	*e*
20		Pecan Bayou, TX	33.74	-95.08	130	Sandstone	1694-1982	*b*
21		Fort Worth, TX	32.86	-97.48	190	Sandstone	1737-1980	*b*
22		Nichols Ranch, TX	32.99	-99.18	425	Sandstone	1681-1995	*b*
23		Leon River, TX	32.18	-98.49	380	Sandstone	1730-1980	*b*
24		Bruck Mountain, TX	33.06	-98.37	427	Sandstone	1774-2006	*b*
25		Fossil Hill, TX	33.45	-97.87	305	Sandstone	1745-2006	*b*
26		LBJ National Grassland, TX[4]	33.36	-97.60	312	Sandstone	1684-2004	*b*
27		Fort Wolters, TX (savanna)[5]	32.84	-98.05	275	Sandstone	1798-2006	*b*
28		Fort Wolters, TX (rocky slope)[5]	32.84	-98.05	275	Sandstone	1793-2006	*b*
29		Kristas Canyon, TX[5]	32.70	-98.17	260	Sandstone	1749-2002	*f*
30		Palo Pinto Wilderness, TX[5]	32.63	-98.27	305	Sandstone	1742-2002	*f*
31	**Ozark**	Little Maries River, MO	38.08	-92.12	350	Limestone	1688-1982	*b*
32		Pomme de Terre River, MO	38.03	-93.34	245	Limestone	1732-1982	*b*
33		Hahatonka State Park, MO	37.97	-92.75	335	Limestone	1660-1982	*b*
34		Democrat Ridge, MO	37.68	-92.01	350	Limestone	1620-1992	*b*
35		White Ranch St. For., MO	37.50	-91.88	280	Limestone	1664-1992	*g*

(…continue…)

Table 1 (...continuation…)

	Ecosystem	Site Name, State*	Lat	Long	Alt (m asl)	Soil	Interval	Ref
36		Mill Mountain, MO	37.13	-91.19	305	Acid Rhyolite/Granite	1693-1992	*h*
37		Clayton Ridge, MO	36.69	-92.82	320	Limestone	1696-1992	*b*
38		Roaring River, MO	36.60	-93.82	425	Limestone	1689-1982	*b*
39		Greasy Creek, MO	37.78	-90.20	275	Granite/Rhyolite	1669-1982	*i*
40		Lower Rock Creek , MO	37.50	-90.50	300	Granite/Rhyolite	1708-1982	*j*
41		Norfork Lake, AR	36.30	-92.20	200	Limestone	1637-1993	*c*
42		Buffalo Park Boundary, AR[6]	36.07	-93.19	335	Limestone	1620-1993	*c*
43		Malcolm's Ridge, AR[7]	36.09	-94.14	440	Sandstone	1679-1992	*c*
44		Wedington Mountain, AR[7]	36.08	-94.41	430	Sandstone	1725-1982	*b*
45		Hemmed in Hollow, AR[6]	36.08	-93.30	550	Limestone	1670-1992	*c*
46		Point Peter Mountain, AR	35.93	-92.87	580	Limestone	1692-1993	*c*
47		Old Growth Study, AR	35.83	-94.05	---	Sandstone	1629-1991	*c*
48	**Post-oak**	Brazos River, TX	30.94	-96.80	105	Sand/Gravel	1668-1995	*b*
49	**Savannah**	Mason Mountain, TX	30.88	-99.19	540	Granite	1677-1995	*b*
50		Red Rock Creek, TX	30.83	-98.52	350	Granite	1735-1982	*b*
51		Yegua Creek, TX	30.32	-96.64	90	Sand/Gravel	1658-1995	*b*
52		Capote Knob, TX[8]	29.49	-97.79	170	Sandstone	1712-1982	*b*
53		Lavaca R., TX	29.31	-96.96	75	Sandstone	1668-1995	*b*
54		Ecleto Creek, TX[8]	29.44	-97.92	230	Sandstone	1695-1996	*c*
55		Coleto Creek, TX	28.76	-97.18	35	Sandstone	1682-1995	*b*

*numbers indicate sites with same climate time series. References: **a:** STAMBAUGH; GUYETTE, 2007; **b:** STAHLE et al., 1985; **c:** University of Arkansas, Tree-Ring Laboratory (unpublished); **d:** DESANTIS et al., 2009; **e:** STAMBAUGH et al., 2008; **f:** PEPPERS, 2004; **g:** STAHLE et al., 2005a; **h:** STAHLE et al., 2005b; **i:** DUVICK, 1994a; **j:** DUVICK, 1994b.

The numerical tree-ring chronologies were recomputed for this study using the program ARSTAN (COOK, 1985), (version 41d10.5; also available at: http://www.ltrr.arizona.edu/software.html). All raw ring-widths series were detrended and standardized using a smoothing spline with a 50% frequency response of 100 years (COOK; PETERS, 1981). Standardization is a basic procedure in dendrochronology and involves the fitting of a smooth growth curve to each raw ring-width series to remove long-term growth trends associated with increasing tree age and tree size. The raw ring widths are divided by the fitted curve at each year to compute the ring width indices with trend removed and a mean and variance that are more homogeneous with respect to time (FRITTS, 1976). The standardized ring-width indices for each core were then averaged on an annual basis to compute the mean index chronology for each site, using robust estimation of the mean to discount statistical outliers (COOK, 1985).

For each collection/site, a mean chronology, which will be referred to as residual chronology, was calculated using robust estimation followed by variance stabilization with a 100-year spline. This way, inter-annual and multi-decadal variability were still maintained (see APPENDIX A). Among the primary outputs of ARSTAN program is also the standard chronology, which is the mean chronology of tree-ring indices before the autoregressive modeling used to remove low order growth persistence and originate the residual chronology. The standard chronology maintains some low order growth persistence and may present an amount of coherent tree growth variability. The tree-ring chronologies ranged from 209 to 385 years in length, between 1611 and 1995 (Table 1). From this overall set, all chronologies covered the common time period 1798 – 1980 (183 years).

2.2 The PDSI and Z-index

Palmer Drought Severity Index (PDSI) and Palmer Moisture Anomaly Index Z (PALMER, 1965) were both obtained for each site using gridded values computed for North America based on station precipitation and temperature data interpolated to the 0.5° grid that extends from 1895 to 2005 (Richard Heim, National Climatic Data Center, NOAA, personal communication). The dataset is still under development and was created from a high-quality suite of 5639 temperature and 7852 precipitation data records from across the United States, Canada, and Mexico. The PDSI is a well-known and widely used soil moisture balance index that models long-term meteorological drought and wet conditions, providing a reasonable approximation for the climate forcing of tree growth (COOK, 1999). PDSI values are cumulative in nature and present a strong month to month autocorrelation, so the intensity of drought during the current month is dependent on the current weather patterns plus the cumulative patterns of previous months (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 2010).

The monthly moisture anomaly index (Z-index) represents the departure of the moisture supply from normal on a monthly scale (both temperature and precipitation), providing comparable measures of relative short-term climatic abnormalities (PALMER, 1965) with no month to month autocorrelation. There is a peak correlation between June PDSI and tree rings in the southcentral United States (STAHLE; CLEAVELAND, 1988) that can be related to timing of tree growth and to the time required for evapotranspiration demand to significantly draw down soil moisture supply (COOK, 1999). Therefore, June PDSI and June Z-index values were extracted from the dataset for 44 grid points which were the closest to all 55 tree-ring sites.

2.3 Regular and Rotated Principal Components Analysis

Regular Principal Components Analysis (PCA) and varimax Rotated Principal Components Analysis (RPCA) were used to analyze both tree growth and climate using R version 2.11.1. The PCA is based on a decomposition of the correlation matrix computed between the variables (e.g., 55 tree-ring chronologies). This way, PCA reduces a data set containing a large number of variables to a data set containing fewer new variables (principal components, PCs) that represent the maximum possible fraction of the variability contained in the original data and are uniquely defined by the eigenvectors of the correlation matrix of the original data (WILKS, 2006). In regular PCA, the first eigenvector points in the direction in which the data vectors jointly exhibit the most variability, and is associated with the largest eigenvalue. The subsequent eigenvectors are constrained to be perpendicular to all previous eigenvectors as the associated eigenvalues gradually decrease in magnitude (WILKS, 2006).

When physical interpretation rather than data compression is the primary goal of PCA, it is often desirable to rotate a subset of the initial eigenvectors to a second set of new coordinate vectors. The orthogonality constraint on the eigenvectors can lead to interpretation difficulties (RICHMAN, 1986), especially for the second and subsequent PCs that must be orthogonal to previously determined eigenvectors regardless of the nature of the physical processes that have given rise to the data. Therefore, rotated eigenvectors are less prone to artificial features resulting from orthogonality constraint on the unrotated eigenvectors.

The most commonly used approach to RPCA is the varimax method, which maintains the orthogonality among rotated eigenvectors (RICHMAN, 1986). Previous work has shown that the varimax rotation is an adequate method for representing regional summer drought patterns in the U.S. (COOK et al., 1999), and was used in the subsequent analysis done here. Following the rotation of the eigenvectors, a second set of new variables is defined, called rotated principal components (RPCs). The number of RPCs was determined based on the subjective truncation criteria of the scree graph (WILKS, 2006), where the eigenvalues (or proportion of variance explained) for each principal component are plotted in decreasing order.

In the context of this study, the variables were the tree-ring chronologies and the Z-index grid point located close to each tree-ring site, while the observations were the values associated with each time series. The interpretation of PCA and RPCA outputs takes into account the proportion of variance explained for each principal component (defined by the eigenvalue), the loadings, and scores. The loadings (eigenvalue elements) define the weights for each original variable when calculating the PCs, providing an overview of the importance of the variables (LOHNINGER, 1999). The loadings for each chronology location were plotted geographically to ascribe spatial interpretations to the correspondent principal component. Isolines were designed with SURFER 7.0 using the radial basis function with the multiquadric model considering that the events were isotropic. The scores are basically the projection of the data to the new coordinate system which is spanned by the eigenvectors (LOHNINGER, 1999). The PC and RPC score time series were compared using the Pearson correlation coefficient to measure the strength of the linear relationships between principal components computed from climate and tree growth data.

2.4 Data-sets

Four data sets were analyzed to address the scientific questions proposed (Table 2). The first two data sets (A and B) aimed to compare the spatial distribution of major variance patterns for both climate and tree growth for an 86-yr common period (1895 – 1980). Residual chronologies and June Z-indices were chosen to represent tree growth and climate, respectively, because both time series are expected to present no autocorrelation (as described previously). After this first approach, a subsequent analysis searched for patterns related to regional tree growth variability after removing the climate signal. Thus, a third data set (C) was generated by calibrating the standard ring-width chronology with the instrumental June PDSI series for each location using bivariate regression for the same 86-year common period (1895-1980). June PDSI was chosen instead of Z-Index because it represents the best composite of the monthly drought signal strongly expressed in the regional tree-ring data (STAHLE; CLEAVELAND, 1988). After the predictor PDSI time series and the predictand chronology were modeled, the regression residuals time series for each site were used to run PCA and RPCA. Finally, a temporal analysis was conducted for a 200-yr time span and aimed to determine if the spatial patterns observed for tree growth were stable over time. To enable a larger time span, a total of 48 sites with tree-ring series that covered a period from 1751 to 1950 were selected. The residual tree-ring chronologies were subdivided into four 50-yr intervals (1751-1800, 1801-1850, 1851-1900, and 1901-1950) that composed the fourth data set (D).

Table 2 Summary of the data sets design and strategy to address the scientific questions.

Data sets	Question addressed
A) Residual Chronologies for 55 sites (1895-1980) **B)** Z-index series for 44 grid points (1895-1980)	Can the most important spatial patterns of tree growth be explained by spatial patterns in growing season climate, or are there other major forcing factors such as biogeography and soil type (data sets A and B)?
C) Signal free tree-ring chronologies for 55 sites after removing the variation related to June PDSI (1895-1980)	Is there any correlated regional tree growth variability after excluding the growing season climate signal, which might be related to other environmental signals (e.g., phenology, disturbance, soils)?
D) Subsets of residual chronologies, 48 sites (50-yr intervals from 1751-1950)	Are the spatial patterns and fractional variance of tree growth stable over time?

3 RESULTS AND DISCUSSION

PCA and RPCA are powerful tools for spatially decomposing climate and tree-ring data into natural regional patterns and are presented below.

3.1 Spatial patterns of climate and tree growth from 1895-1980

The proportion of variance for PCA, for both the Z-index and the residual tree-ring chronologies, are plotted in decreasing order of the corresponding PC (scree graph, Figure 2).

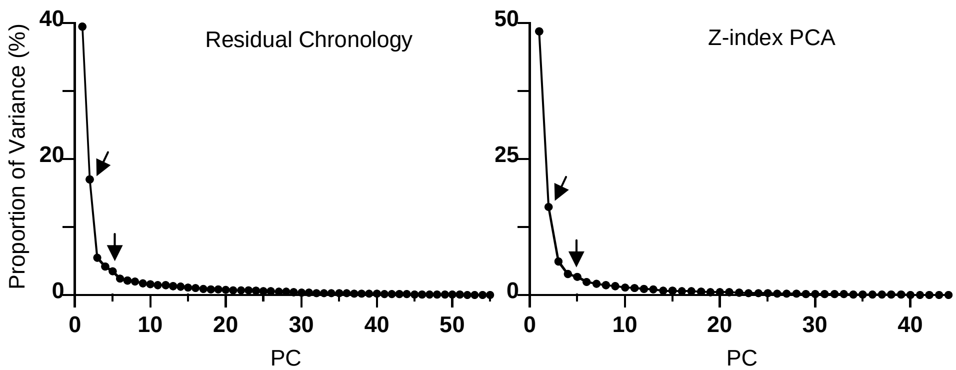

Figure 2 The scree graphs display the proportion of variance related to the eigenvalue of each PC, for the tree-ring residual chronologies (with a 55 dimensional analysis), and for the June Z-index (with a 44 dimensional analysis). The percent variance related to each eigenvalue is obtained by dividing that eigenvalue by the sum of all eigenvalues and multiplying by 100. Arrows point to the second and fifth PCs that were taken as the truncation cutoff for further RPCA

The scree graph is commonly used as one of the subjective approaches to truncating principal components by visually locating a point that separates a steeply sloping portion to the left, and a shallower sloping portion to the right (WILKS, 2006). The total number of PCs corresponds to the number of variables (55 residual chronologies and 44 grid point values for June Z-index). Both Z-index and mean residual chronologies presented a very similar variance spectrum (Figure 2), with the two first principal components accounting for a large portion of the data variance and very low magnitudes of variance starting from the 4^{th} PC. The least important eigenvectors express only minor variations on the original data, some of which result from errors, noise, and residual variations imposed by the mathematical constraints in deriving the eigenvectors.

The loadings of the tree-ring chronologies and gridded Z-indices on the first five principal components are mapped for the southcentral United States in Figure 3, from 1895 to 1980. Together, these five PCs accounted for a cumulative variance of 70% and 78% for tree growth and climate, respectively. The patterns, and not the signs, formed by the loadings are of importance. The first principal components of both tree growth and climate (the Z-index, Figure 3) display a north-south pattern, but there are minor differences in the northern portion of the study area. The second and third principal components presented a very similar spatial pattern for both the tree-rings and the Z-index time series, with a clear northeast-southwest (PC2) and northwest-southeast (PC3) distribution. Together, PCs 4 and 5 accounted for only 7% of total variance and presented a complex spatial pattern. The spatial pattern observed in PC4 for the residual chronologies seemed to be a better match with PC5 for the Z-index, and PC5 for tree-rings is more similar to PC4 for Z-index (Figure 3 and Table 3). Correlation coefficients for the PC score time series are presented in Table 3.

Since the underlying processes involved in both soil moisture availability and tree growth mechanisms are not independent, it is possible that the first PC, which represents an important mode of variability, may also include aspects of other correlated modes. Thus, the orthogonality constraint of regular PCA can result in the influence of several distinct physical and biological processes being represented by a single principal component (WILKS, 2006). In this case, RPCA can help improve the interpretation of geographically plotted loadings by rotating the axes of a retained subset of unrotated principal components in order to achieve some degree of simple structure among variables.

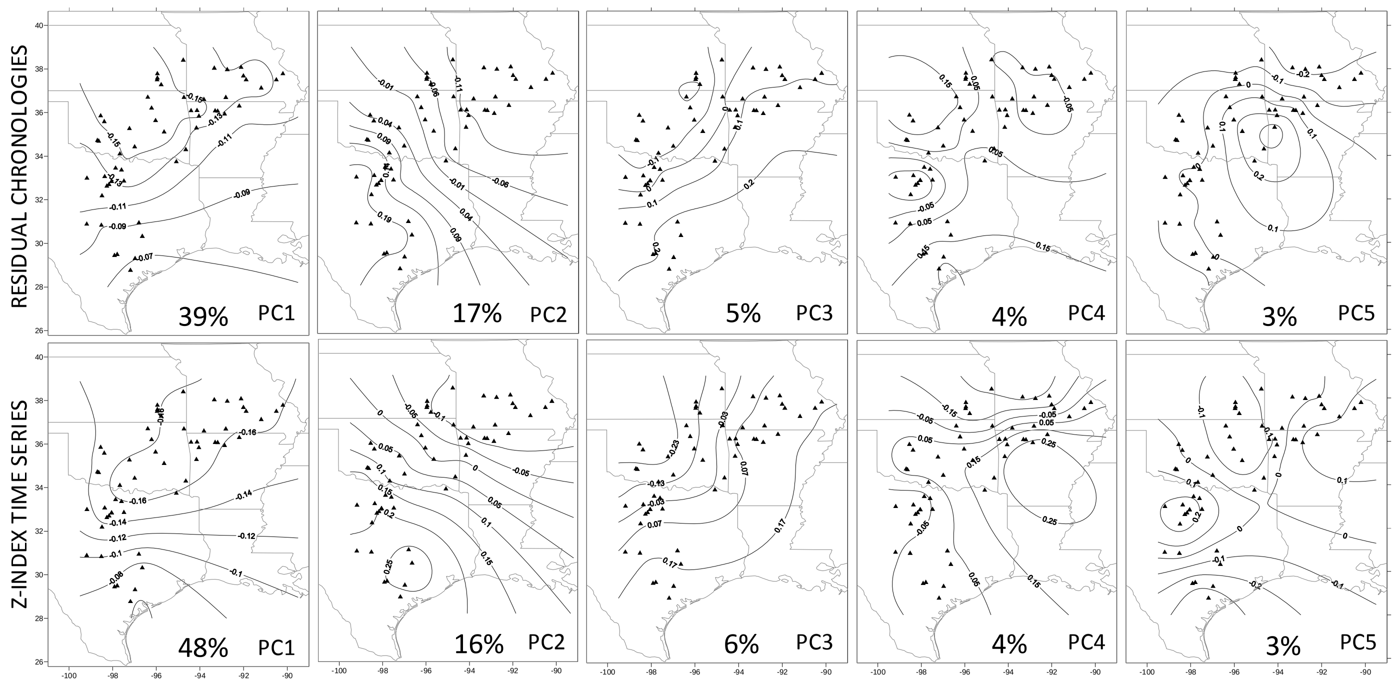

Figure 3 Principal component loadings for the study area (1895-1980) are mapped for the tree-ring data (top row) and for the June Z-index (bottom row). The percent variance accounted for by each PC is indicated on the maps

The results of eigenvector rotation can depend on how many of the original eigenvectors were selected for rotation, and unfortunately it is often not clear how many of the original eigenvectors should be rotated. Here, rotation was conducted for both five and two of the original eigenvectors, based in the criterion of variance fraction retained and natural breaks detected using the scree graph (see arrows, Figure 2). Most of the variance is accounted for using 1 and 2 PCs, and there is a clear drop off on the variance spectrum after PC5.

Figure 4 shows the contour maps for RPCA loadings obtained from the rotation of the first five original eigenvectors. The first rotated principal component is no longer that linear combination of the original data with the largest variance. The variance represented by the original unrotated eigenvectors is spread more uniformly among the rotated eigenvectors, so that the corresponding variance plot is flatter (not shown). The tree growth pattern observed for RPC1 is now more closely parallel to the moisture anomaly pattern (RPC1), and appears to reflect the northeast to southwest aridity gradient (Figure 4). The other RPCs of tree growth, especially RPC2, 3 and 4, appear more closely related to the corresponding RPCA loadings of the Z-index (Figure 4).

The fourth RPCs could be related to the north-south temperature gradient. Temperature data are embedded in the Z-index which incorporates both precipitation (rain or snow water equivalent) and temperature data (transformed into water lost through evapotranspiration) (COOK et al., 2007; PALMER, 1965). Previous work in this region has demonstrated that post oak radial growth is directly related to precipitation and inversely related to temperature (STAHLE; HEHR, 1984).

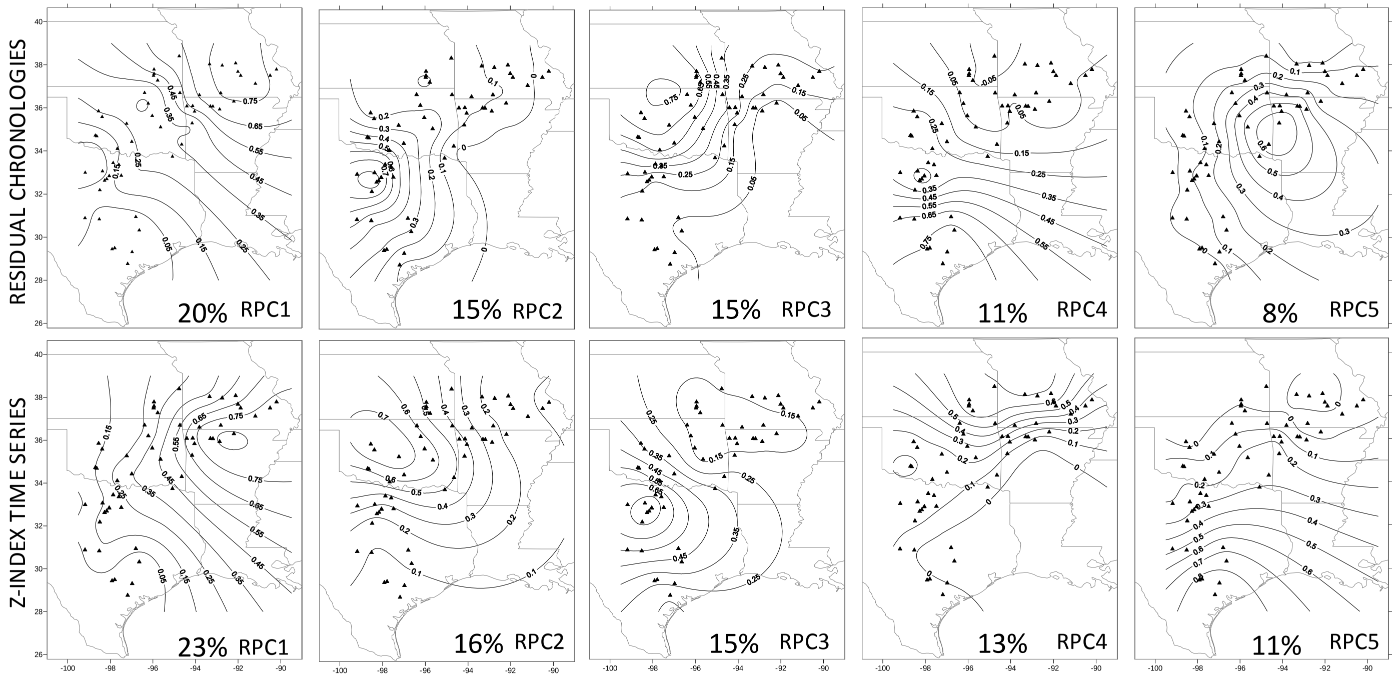

Figure 4 Varimax rotated principal component loadings for the study area (1895-1980) are mapped for the tree-ring data (top row) and for the June Z-index (bottom row). The percent variance accounted for by each RPC is indicated

Table 3 Correlations between principal components from PCA and RPCA, for residual chronologies and Z-index time series

			RESIDUAL CHRONOLOGIES				
		PCs	1	2	3	4	5
Z-INDEX TIME SERIES	**Regular PCA**	1	**0.674****	0.214	-0.065	-0.021	0.198
		2	-0.175	**0.467****	0.131	0.066	0.125
		3	0.048	-0.019	**0.391** **	-0.007	-0.089
		4	-0.039	-0.163	0.191	0.166	0.166
		5	0.048	-0.125	0.020	-0.223 *	0.025
	Rotated PCAs	1	**0.583****	-0.148	-0.001	0.009	0.120
		2	0.185	0.076	**0.419** **	0.026	0.136
		3	0.167	**0.308****	0.069	0.126	0.074
		4	0.228*	0.146	0.190	-0.113	-0.185
		5	0.049	0.110	0.053	**0.493** **	0.065
		1	**0.643****	-0.06			
		2	0.231*	**0.527****			

** Significant at the 0.01 level; * significant at the 0.05 level

When rotating just two eigenvectors (Figure 5), the major spatial patterns of tree growth and growing season climate are very similar (Table 3), probably reflecting different polarities of the aridity gradient. This dominant climate pattern was clearly evident in all previous displays and agrees with the regional drought pattern described in Cook et al. (1999), based on the varimax rotation method with PDSI data. Other extensive tests using RPCA revealed that tree-ring reconstructions contained the large-scale features of drought variability found in the instrumental data (COOK et al., 1999; KARL; KOSCIELNY, 1982; MEKO et al., 1993). A visual comparison of the equivalent varimax RPCs in Figure 4 and 5 indicates that the tree-ring data have indeed captured the regional summer drought climatology in the southcentral U.S. very well.

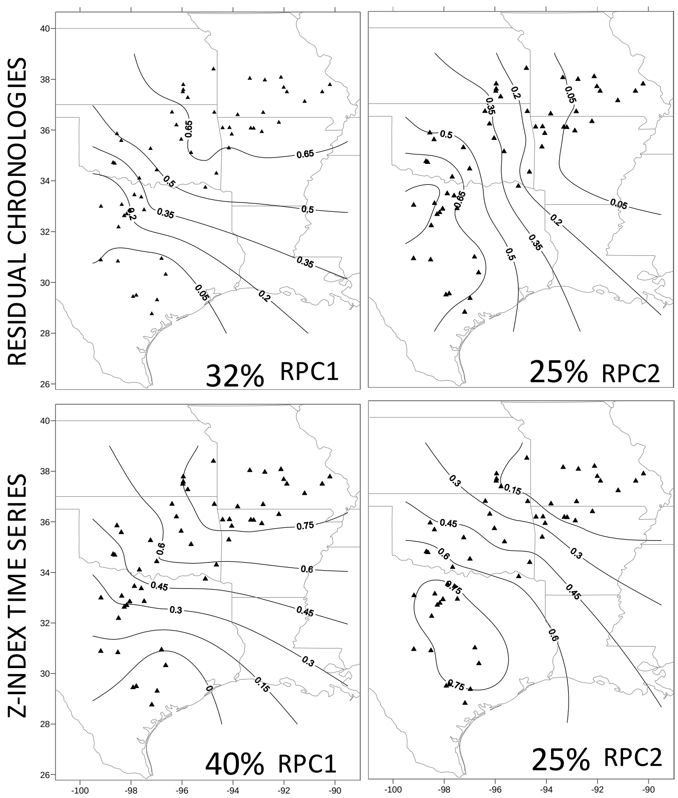

Figure 5 Varimax rotated principal component loadings for the study area (1895-1980) are mapped for the tree-ring data and for the June Z-index. The percent variance accounted for by each RPC is indicated

The scores for the first and most important PC/RPCs are plotted against the corresponding years (Figure 6). The time series express how well the spatial patterns of tree growth and Z-index match over time. If the amplitude is large and positive, the original data resemble the eigenvector in a direct manner (the reverse is also true). If the amplitude value is zero, the eigenvector is uncorrelated with the data for that year. The average time series of all 55 residual chronologies and all 44 June Z-indices are also plotted (Figure 6E) to facilitate comparison.

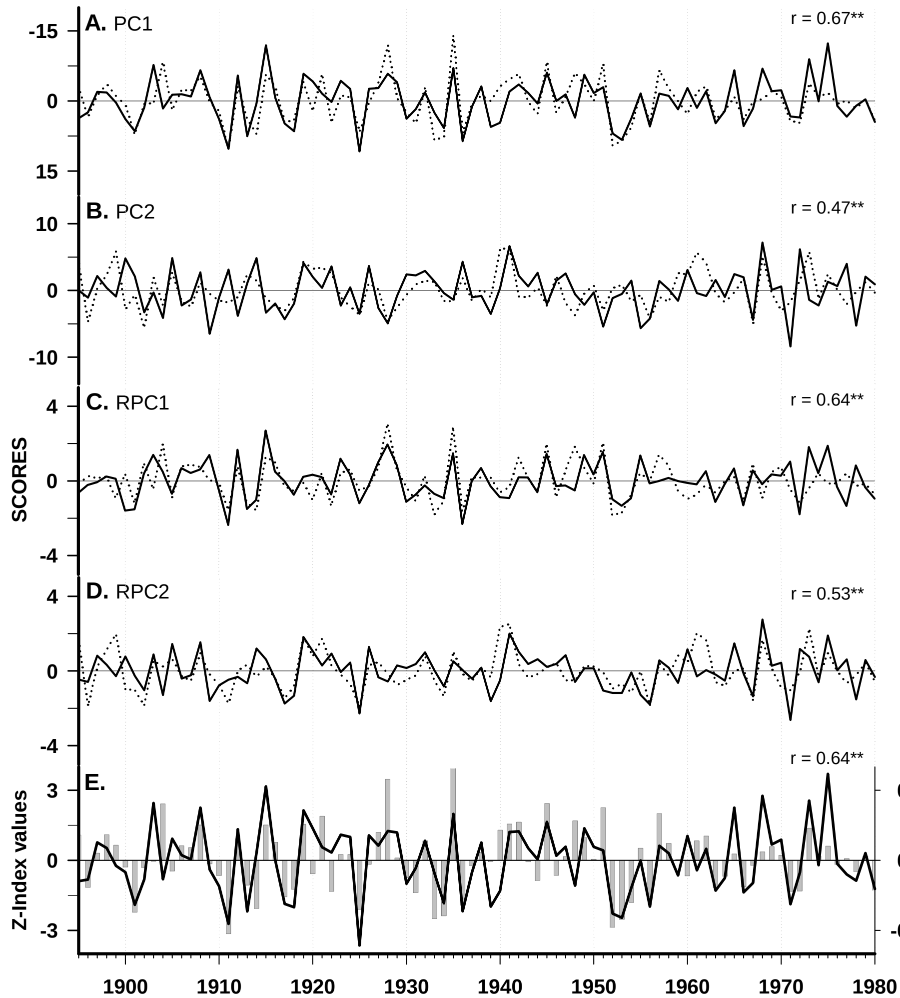

Figure 6 Score time series of the first two principal components of PCA (A and B) and RPCA with two rotated eigenvectors (C and D). The solid lines indicate the tree-ring data, while dotted lines indicate the scores based on the June Z-indices. Percentage values are the correlation between time series according to Table 3. Bottom time series (E) is the region wide average of all 55 residual chronologies (solid line) and all 44 June Z-index time series (gray bars) without PCA. Sign does not have physical meaning, and to highlight drought and low growth periods on PC1 the Y-axis was inverted to synchronize the data peaks

The scores amplitudes generally agreed with the original data for growth and climate, including documented regional June droughts, such as 1911, 1925, and the prolonged drought from 1951 to 1956 (STAHLE; CLEAVELAND, 1988). The score time series analysis enabled to detect that the different sense of the spatial patterns observed for RPC1 and RPC2 (Figure 5) are straightly related with soil moisture anomalies. Years with high scores for RPC1 were associated with very wet (high positive Z-Index values) for sites located in the northeastern part of the study area, and low positive Z-Index values for sites in the southwest. The opposite was also true: years with low scores (RPC1) were associated with very dry conditions in Missouri and southeastern Kansas, and not so dry in south Texas. Oppositely, for RPC2 high and low scores were related with very wet and very dry conditions, respectively, for South Texas. Thus, the two most important modes of variance are related to the aridity gradient, and RPCA was capable to detect two different moisture anomalies (i.e., wet in OK and dry in TX versus dry in OK and wet in TX).

3.2 The climate signal-free spatial patterns of tree growth from 1895-1980

The previous analyses indicate that the spatial patterns of tree growth closely resemble the patterns of growing season moisture availability for the 1895-1980 common period. In addition to growing season climate, regional factors such as phenology (especially differences in the seasonal onset of growth) or disturbances (fire, ice damage, tornados) might cause regional patterns in the radial growth of post oak. To search for regional scale patterns of post oak growth not related to the growing season moisture balance, bivariate regression was used to calibrate each tree-ring chronology with the local June PDSI from 1895 to 1980 (see Table 4 for regression results).

The time series of residuals from the regression of growth on PDSI for each tree-ring site were then submitted to PCA and RPCA to search for spatial structure. The average tree growth variance explained by June PDSI for all sites was R^2=0.37, and varied from a low R^2 = 0.15 to a high R^2 = 0.56 (Table 4). All regression coefficients were significant ($P < 0.05$). The PDSI for the month of June integrates current and prior soil moisture conditions over several months. This enables that one month of PDSI (e.g., June) can be strongly correlated with tree rings even though the trees are usually sensitive to several months of changing moisture supply during a typical growing season (COOK et al., 2007).

Table 4 Percent variance explained (R-square) by the bivariate regression models computed between the standard tree-ring chronologies and the June PDSI at each site. The numbers (N) correspond to the sites in Table 1

N	R^2	N	R^2	N	R^2	N	R^2	N	R^2
1	0.30	**12**	0.46	**23**	0.22	**34**	0.40	**45**	0.51
2	0.40	**13**	0.29	**24**	0.30	**35**	0.44	**46**	0.40
3	0.46	**14**	0.31	**25**	0.33	**36**	0.56	**47**	0.48
4	0.45	**15**	0.15	**26**	0.30	**37**	0.24	**48**	0.42
5	0.34	**16**	0.25	**27**	0.44	**38**	0.53	**49**	0.27
6	0.29	**17**	0.43	**28**	0.51	**39**	0.53	**50**	0.43
7	0.25	**18**	0.32	**29**	0.56	**40**	0.40	**51**	0.51
8	0.27	**19**	0.26	**30**	0.39	**41**	0.37	**52**	0.49
9	0.26	**20**	0.19	**31**	0.19	**42**	0.40	**53**	0.22
10	0.48	**21**	0.42	**32**	0.50	**43**	0.23	**54**	0.45
11	0.16	**22**	0.28	**33**	0.27	**44**	0.32	**55**	0.53

The scree graph from PCA analysis (not shown) indicated a clear cutoff at the second PC which accounted for 35% of total variance. The patterns obtained from RPCA after rotating two eigenvectors are presented in Figure 7. A considerable amount of residual variance was left over after removing the June PDSI climate signal. RPC1 is very close to what would be expected from a phenology driven spatial pattern. The closed contour over the Ozarks matches with the highest altitude sites which tend to initiate radial growth later than lower land and south located post oak trees. RPC2 presented a very interesting spatial pattern that could be related to disturbance. The circled isoline in northcentral Texas resembles the tornado alley zone, and is also a region more prone to fires. Ice storms are more common on the edge of the cross-timbers and could also be influencing the spatial pattern seen in RPC2. These inferences, however, need to be tested with climate analysis beyond the scope of the present study.

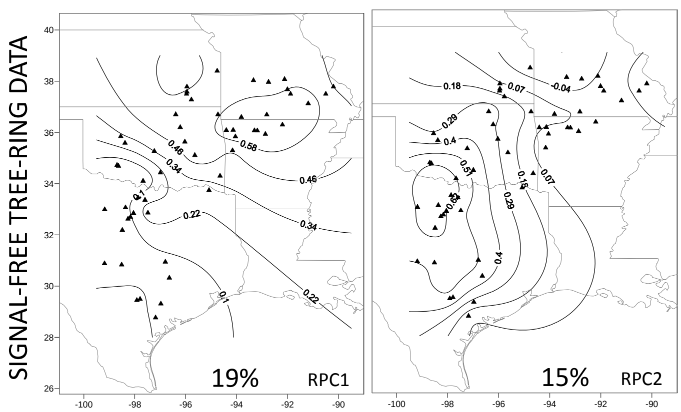

Figure 7 Varimax rotated principal component loadings for the study area (1895-1980) are mapped for the climate signal-free tree-ring data. The percent variance accounted for by each RPC is indicated

Previous studies have indicated that soil could be a predominant factor behind the broad transition zone between upland forest and prairie in the southcentral United States (BRUNER, 1931; DYKSTERHUIS, 1948). Soil texture, through its influence on available moisture supply, together with fertility and depth, would definitely have a pronounced effect over forest composition and productivity. However, the soil information from the data network was not fine grain enough to establish a relationship between soil fertility and spatial pattern of post oak tree growth variation.

3.3 Temporal analysis of tree growth through 1751-1950

A total of 48 sites with tree-ring series that covered a 200-yr period (1751-1950) were selected to check for stability of regional patterns of tree growth over time. The residual tree-ring chronologies were subdivided into four 50-yr subsets: 1751-1800, 1801-1850, 1851-1900, and 1901-1950. Figure 8 shows the variance spectrum obtained from regular PCA conducted for each subset.

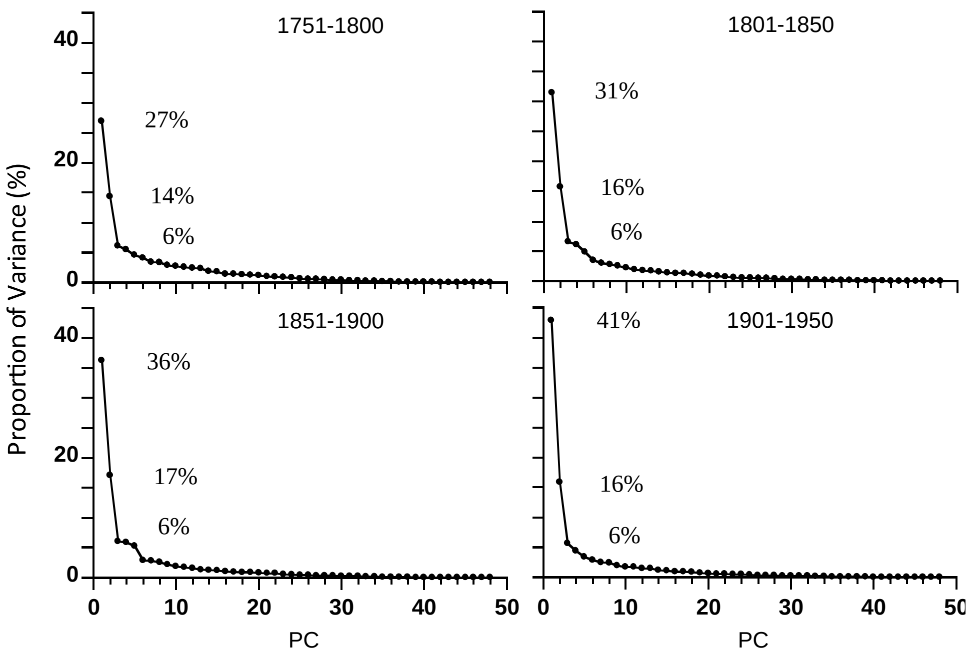

Figure 8 Scree graph displays from PCAs conducted for each subset of periods (1751-1800, 1801-1850, 1851-1900, and 1901-1950). The percent variance related to each eigenvalue is obtained by dividing that eigenvalue by the sum of all eigenvalues and multiplying by 100

The scree graphs for the 50-yr sub-periods were very similar in shape. The cumulative variance from the first 5 PCs gradually increased from 57% (1751-1800) to 72% (1901-1950). What is causing the decline of variation towards the past is uncertain, but could be related with varying degrees of interdecadal variability of the tree-ring chronologies. It could also be related to sample size effect, since it is common to have few single time series of tree-ring measurements that extend to the entire period (in this case, 200 years). This hypothesis could be further tested by returning to the original data and building the site chronologies based only in individual time series than comprise the 200-yr period. Notice that the first two principal components carry the major variance and the difference in magnitude of fractal variance is driven mainly by PC1 (27% to 43%, Figure 8). Based on this behavior, the two first eigenvectors were rotated for all subsets using the varimax method and are displayed in Figure 9.

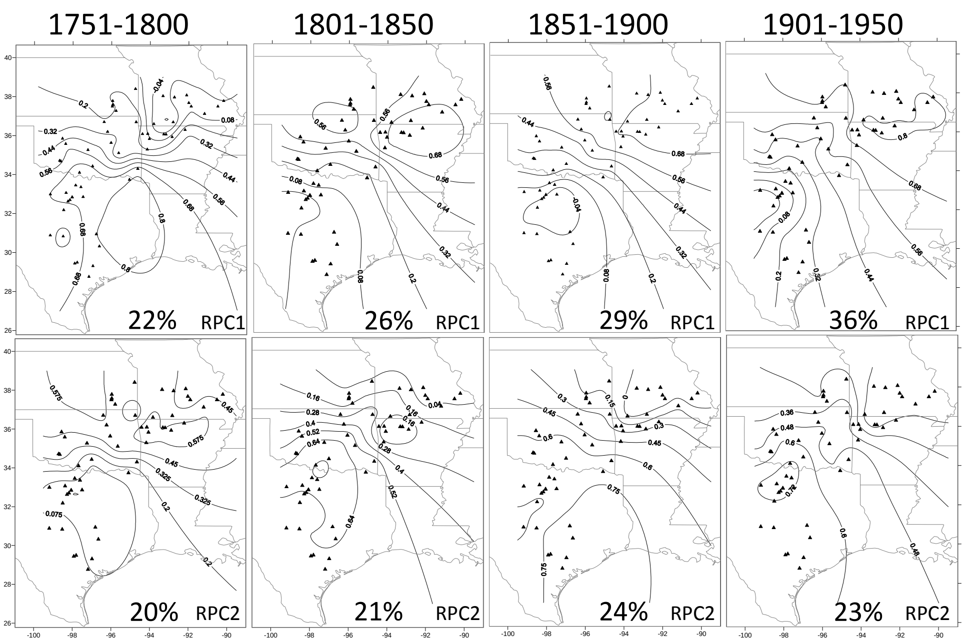

Figure 9 Varimax rotated principal components (RPCs) for each subset of periods from 1751-1950. The percent variance accounted by each RPC is indicated in each map

The temporal analysis showed similar spatial patterns for the non-overlapping 50-yr periods running from 1751-1950 and indicates that the spatial variation of tree growth were stable over time. These results agree with the findings of Stahle and Cleaveland (1988) that reported that tree-ring reconstructed PDSI values during a 50-yr interval period (1931-1980) were representative of the past 283 years for 9 climate sensitive sites from north and southern Texas.

4 SUMMARY AND CONCLUSIONS

The major findings of this research included:

(1) The results of spatial comparisons between the June moisture balance and tree-ring growth indicate that the major spatial patterns of tree growth resemble the major patterns of climate. These tree growth patterns have been widely used to reconstruct the patterns of drought and wetness over North America (COOK et al., 1999; COOK et al., 2007; FRITTS, 1976).

(2) The average tree growth variance explained by June PDSI was $R^2 = 0.37$, with the regression coefficients ranging from $R^2 = 0.15$ to $R^2 = 0.56$ (significant at the 0.05 level).

(3) A considerable amount of residual variance was left over after removing the June PDSI climate signal. The two main modes of variance appeared to be related with plant phenology (post oak seasonal onset of growth) and disturbance (such as tornado, fire, and ice storms). Further climate analysis should be conducted to test these hypotheses.

(4) The cumulative variance from PCAs conducted for the 50-yr sub-periods presented a dramatic increase from 1751-1800 to 1901-1950, driven mainly by PC1 (27% to 43%). The reason for such behavior remains uncertain and needs further clarification.

(5) Temporal spatial patterns of tree growth showed two major modes of variance and appeared to be stable over time.

Future research could contribute to elucidate the actual factors acting upon the spatial patterns of post oak growth not related to soil moisture, given the ecological and environmental importance of theses phenomenon. The climate signal free tree-ring data could also be tested using Z-indices time series averaged to the entire growth season and see if these findings are confirmed. In order to better understand the increase of variance for PCAs conducted on the temporal analysis a new set of "frozen" sample sized tree-ring data should be applied.

Finally, the tree-ring network used here is an outstanding data set, covering a large area (~10^{o} in latitude and 9^{o} in longitude) and located in a broad transition zone of complex ecosystems mosaics and environmental gradient. The network offers a unique quantitative means to address important ecological, climatic and other environmental problems, and enables the extension of short term observations into the past hundreds of years.

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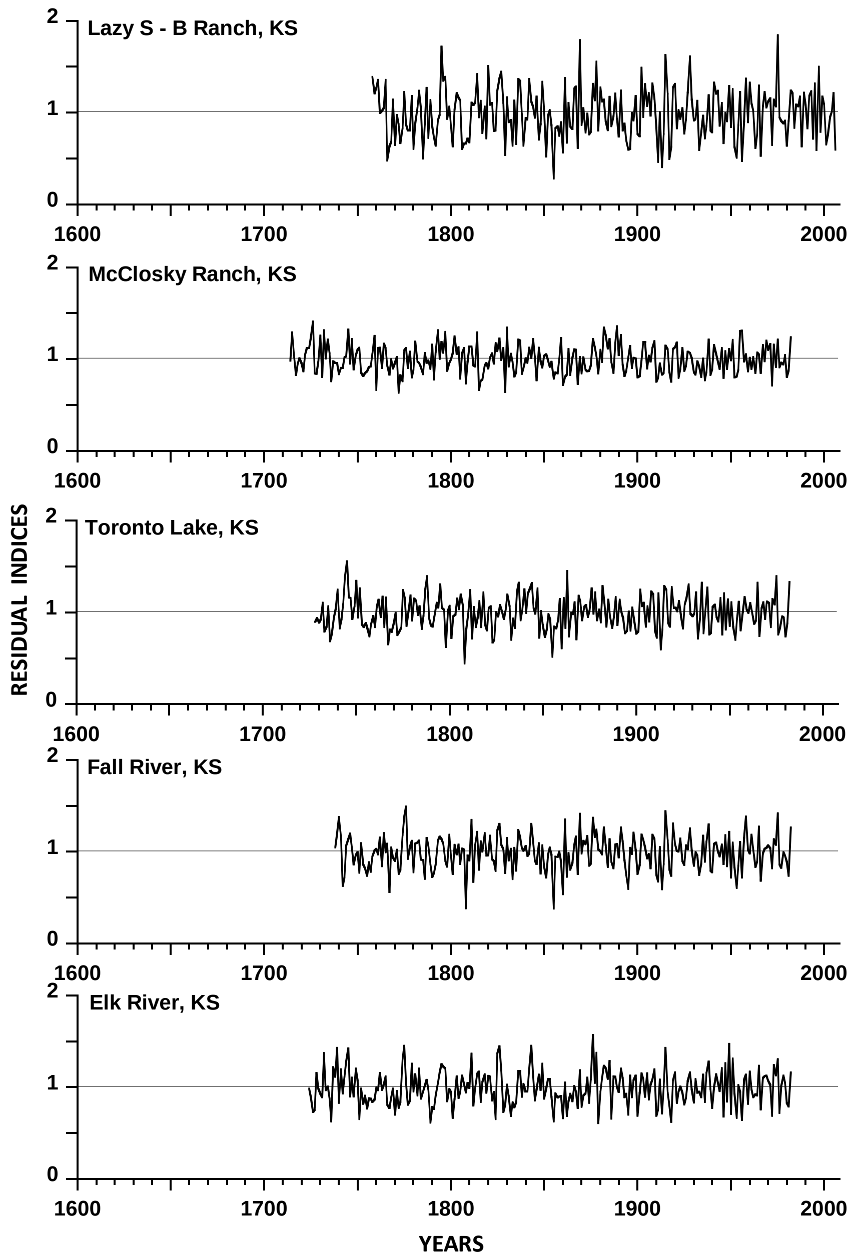
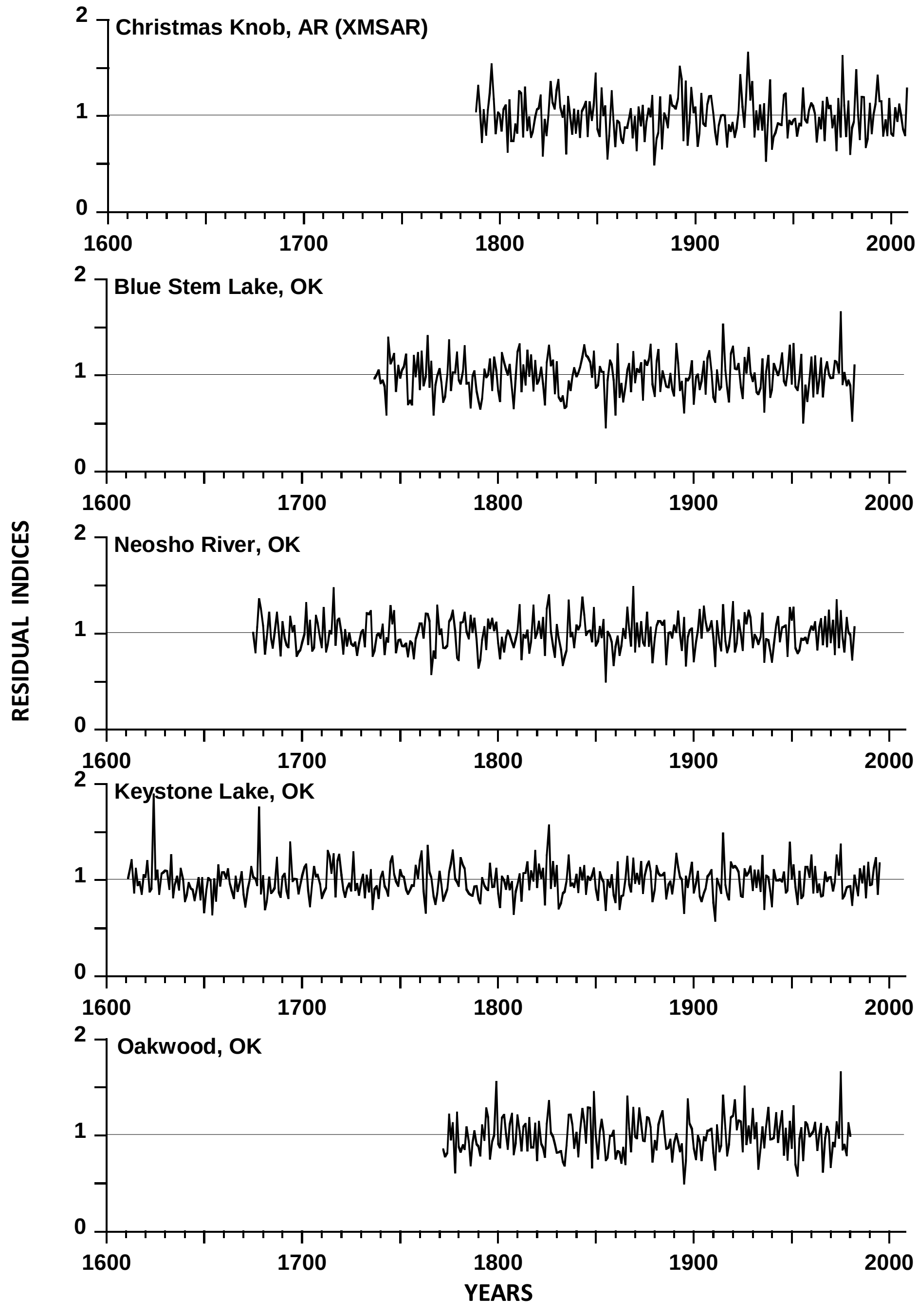
APPENDIX

APPENDIX A – Residual chronologies for the 55 sites from this study.

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Neosho River, OK
Keystone Lake, OK
Oakwood, OK
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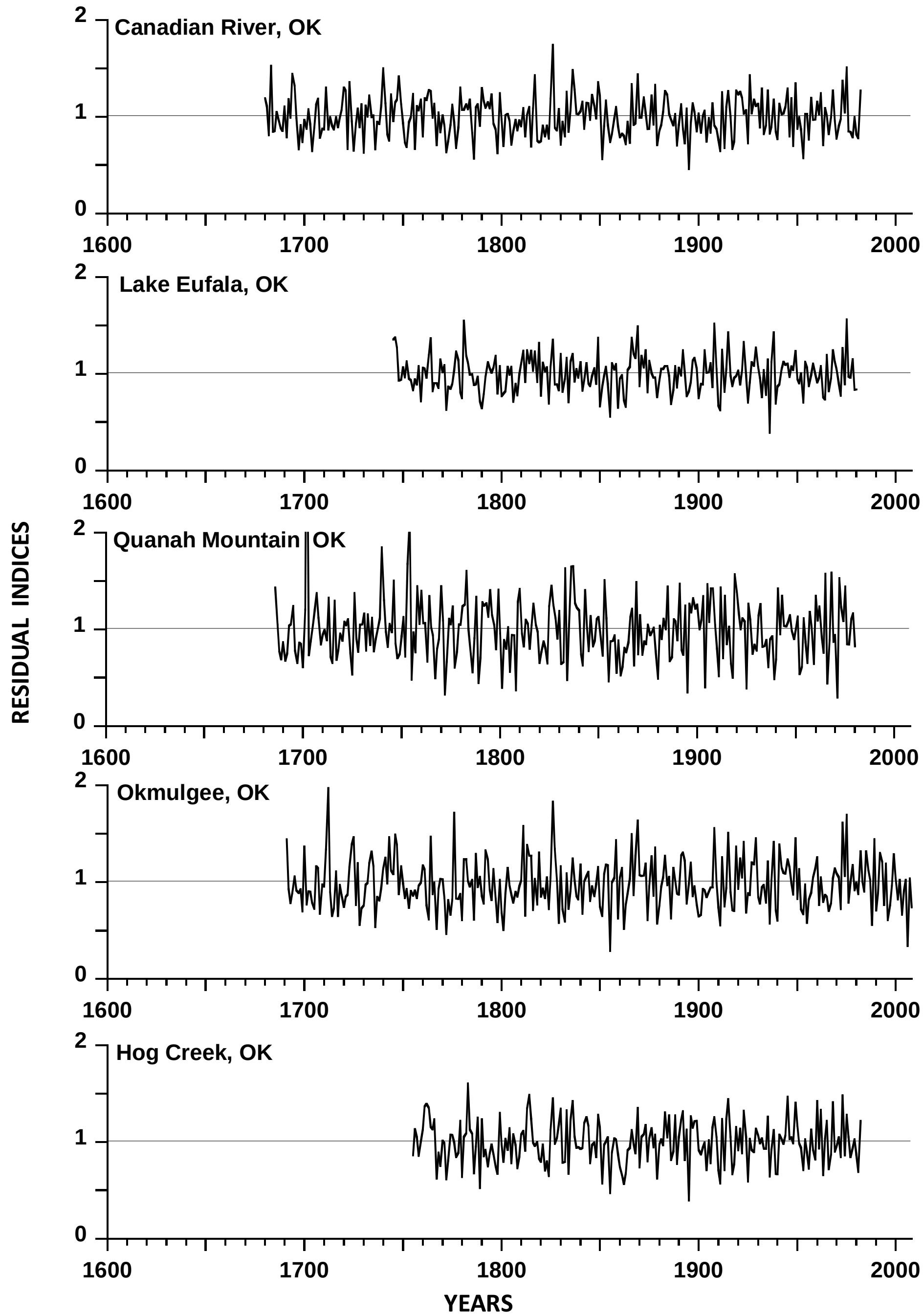
2
1600
1700
1800
1900
2000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YEARS
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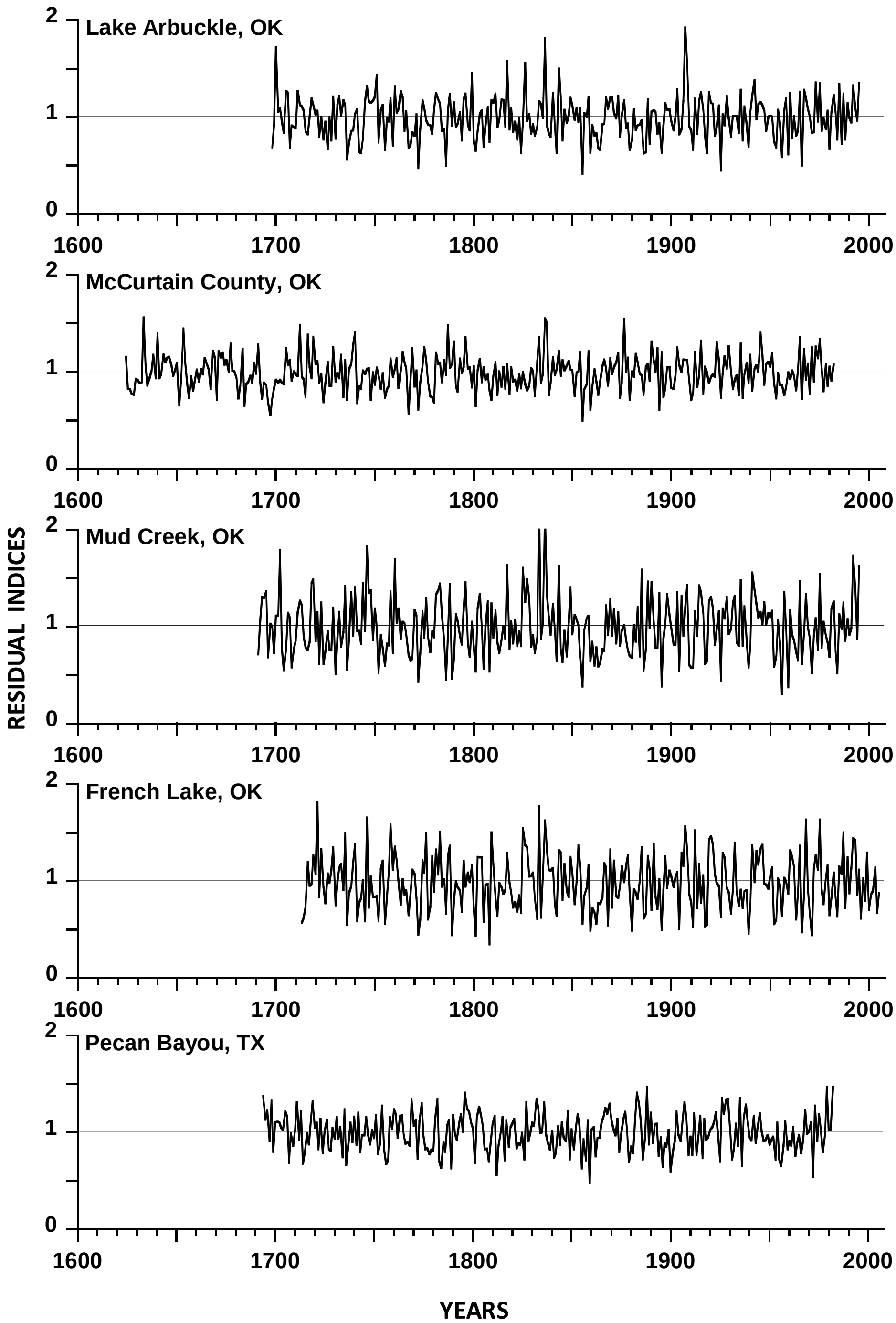
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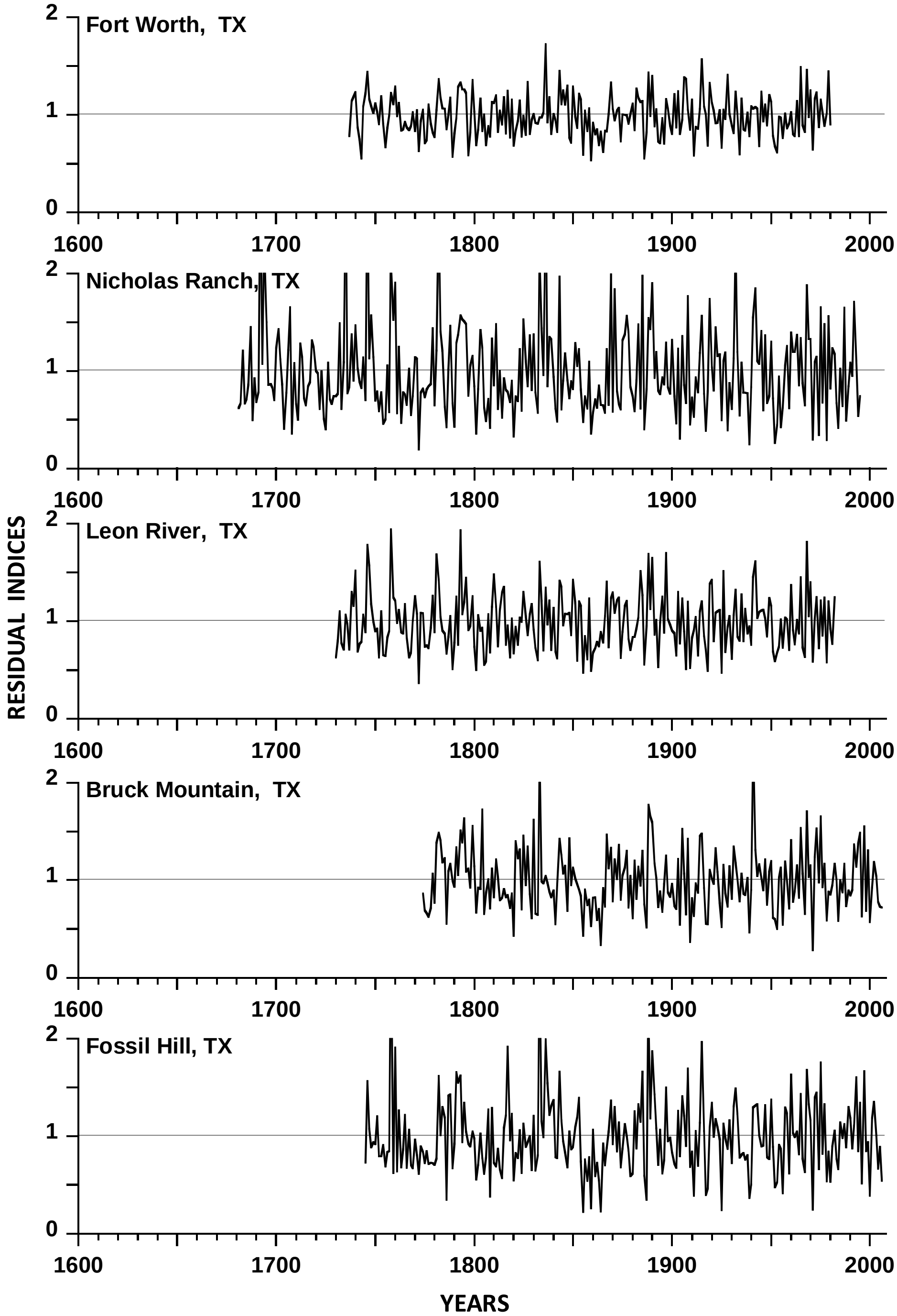
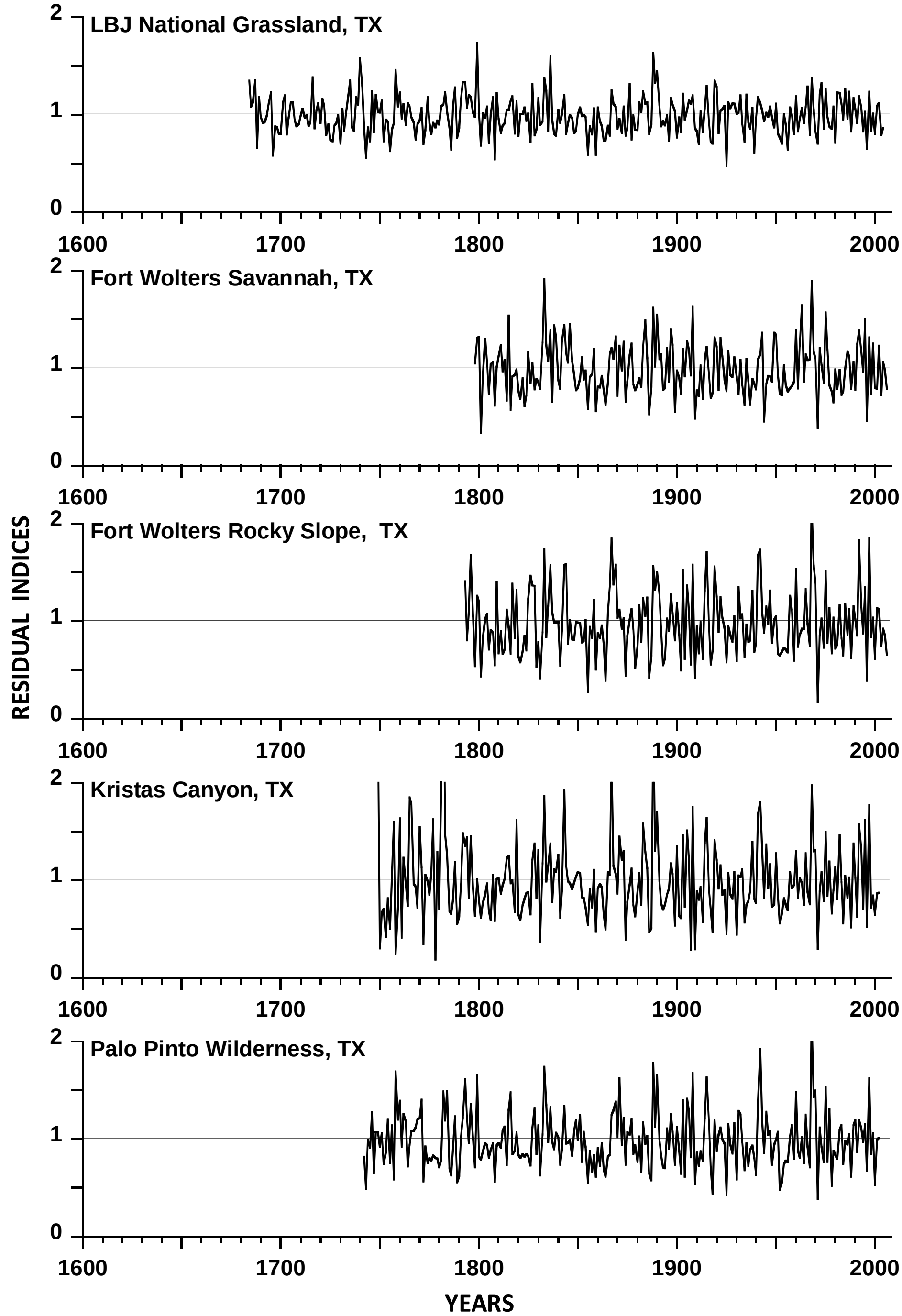
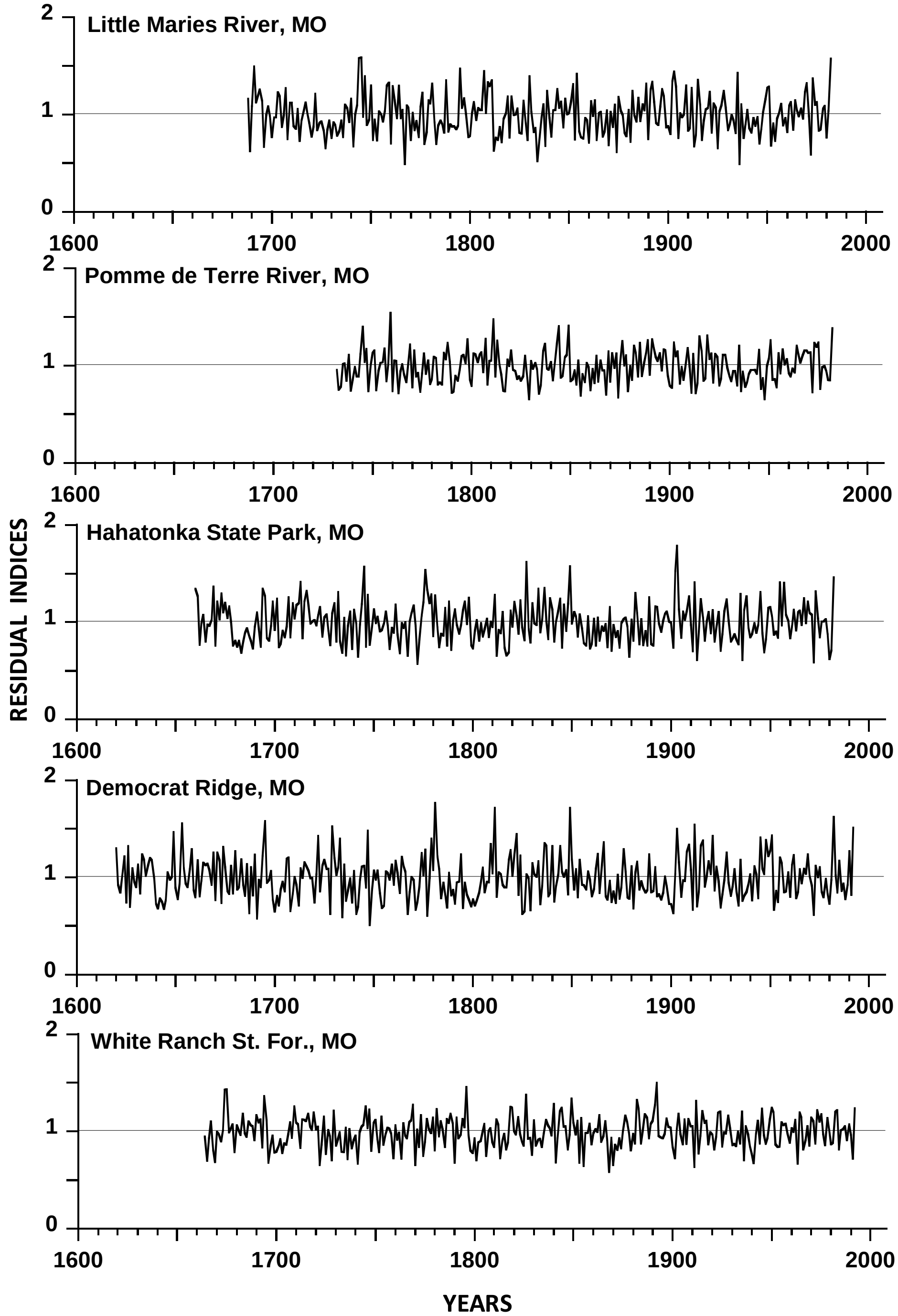
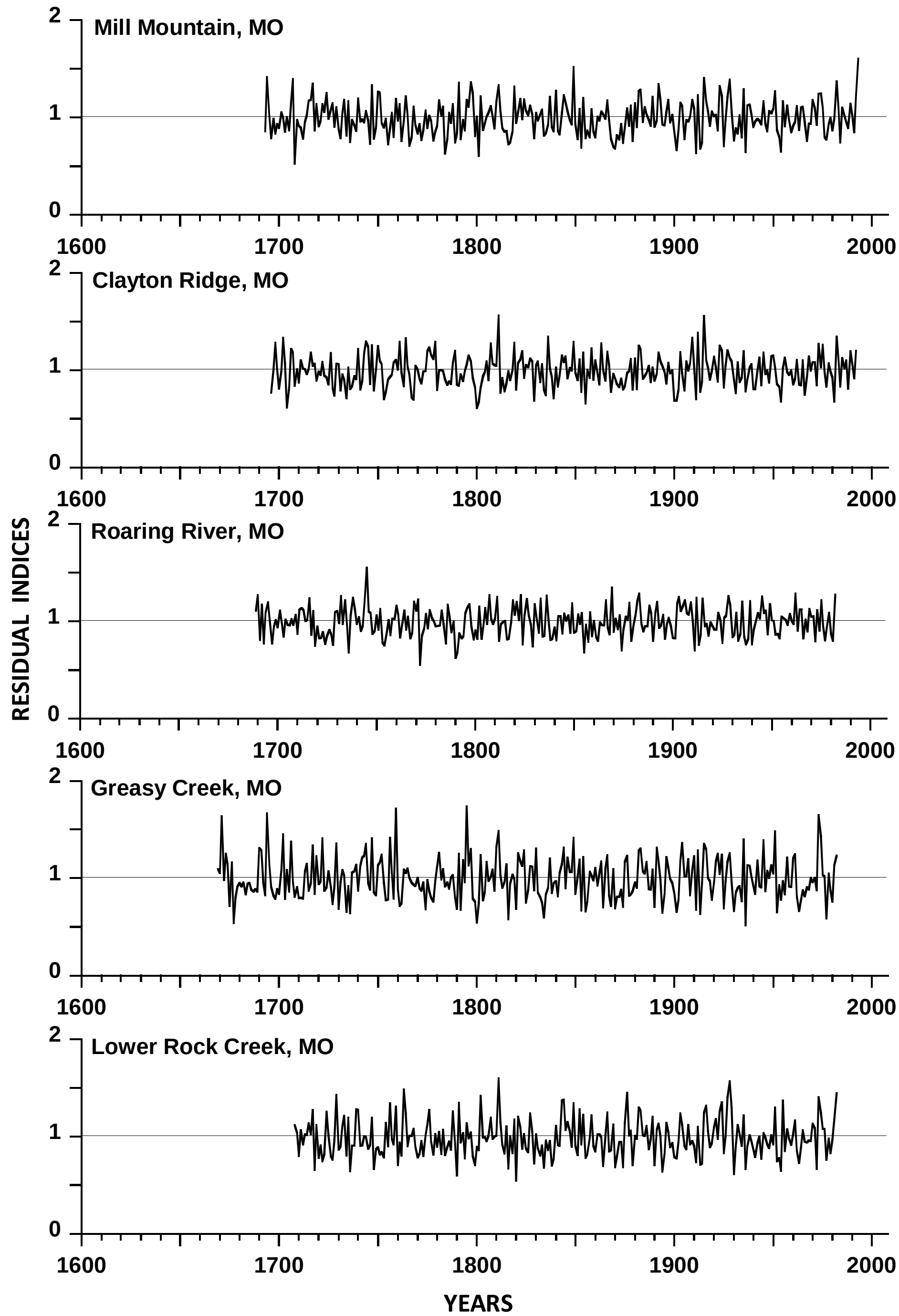
McCurtain County, OK
Mud Creek, OK
French Lake, OK
Pecan Bayou, TX
RESIDUAL INDICES
YEARS
0
1
2
1600
1700
1800
1900
2000

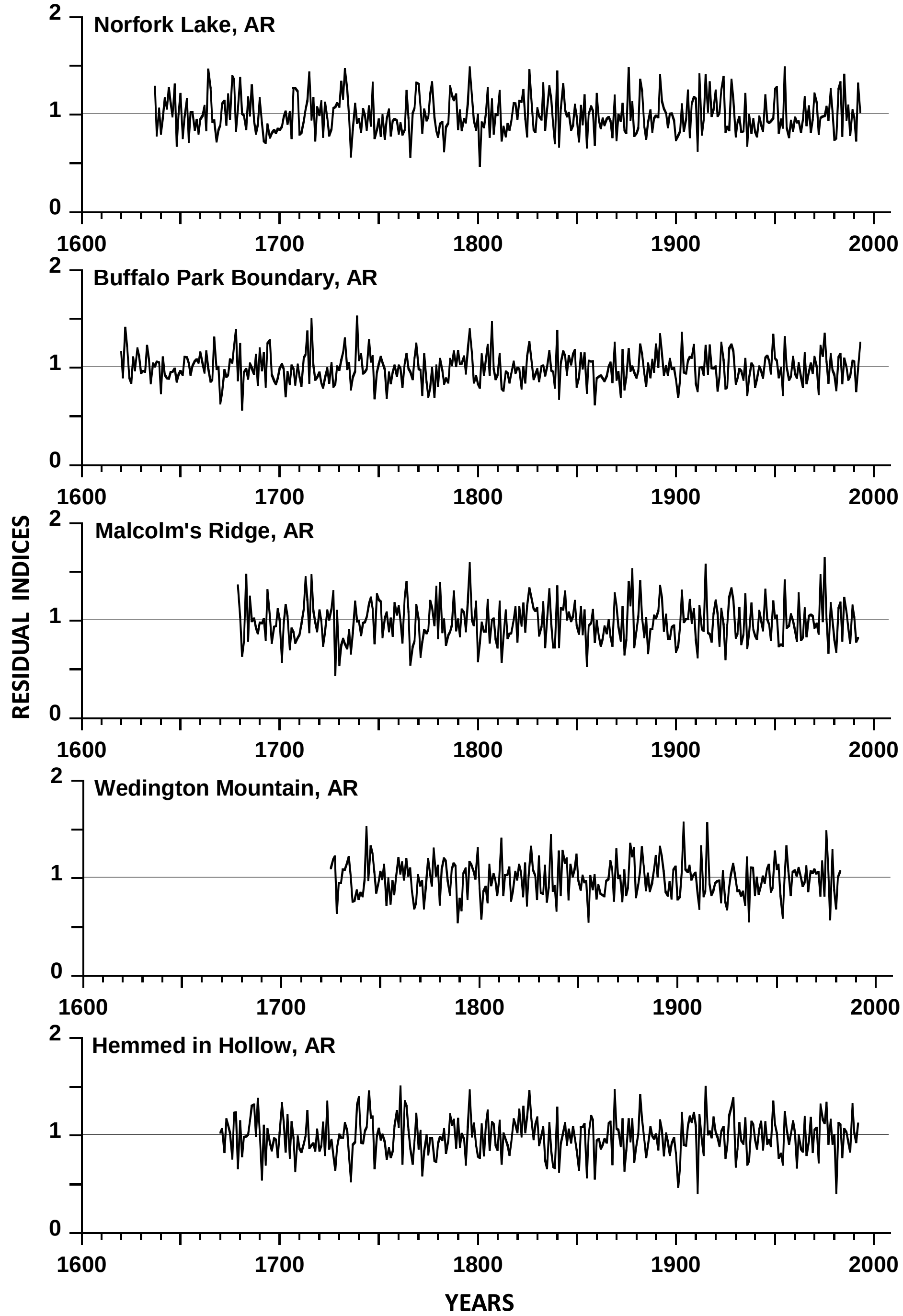


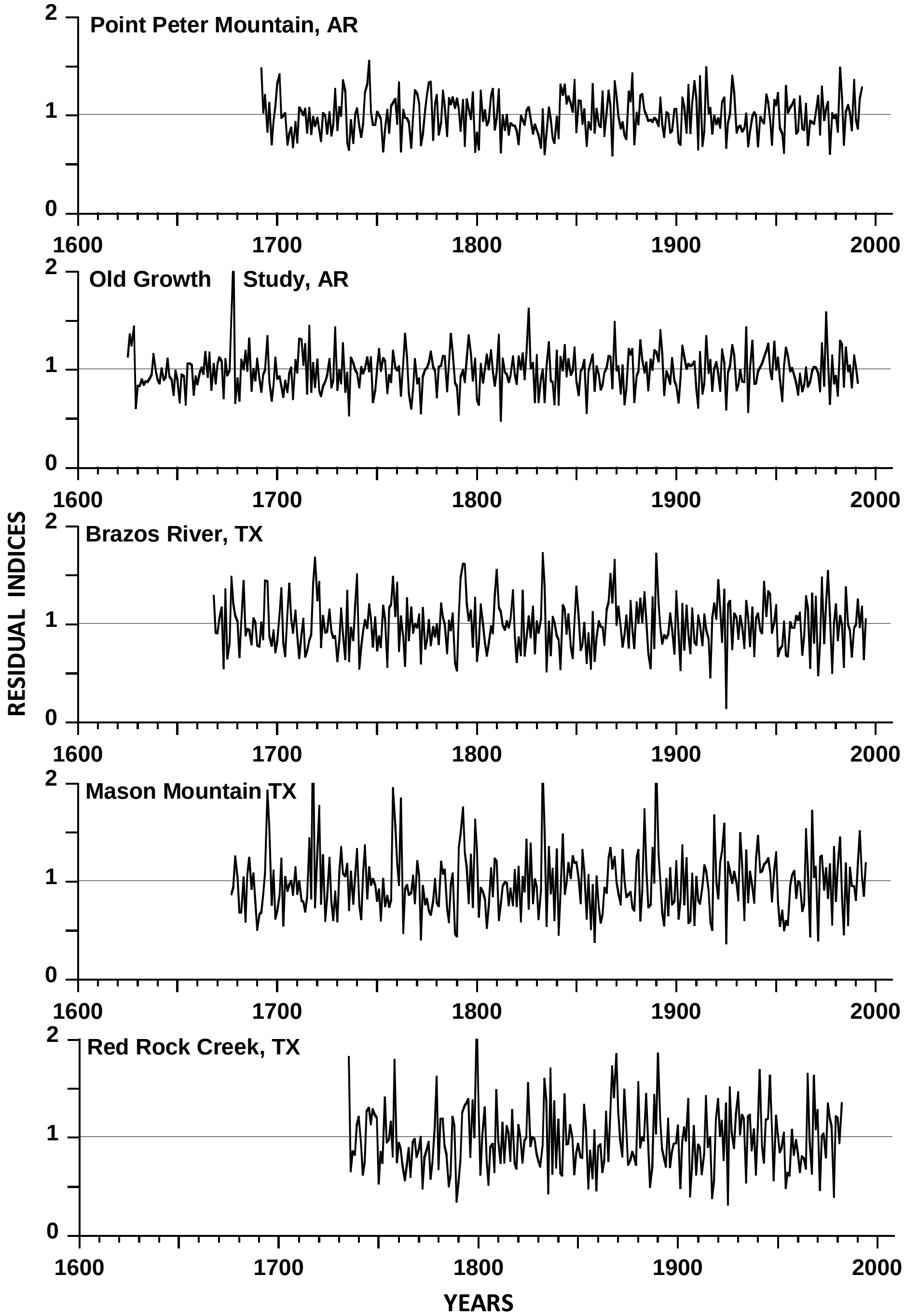
Fort Worth, TX
Nicholas Ranch, TX
Leon River, TX
Bruck Mountain, TX
Fossil Hill, TX
RESIDUAL INDICES
YEARS
0
1
2
1600
1700
1800
1900
2000

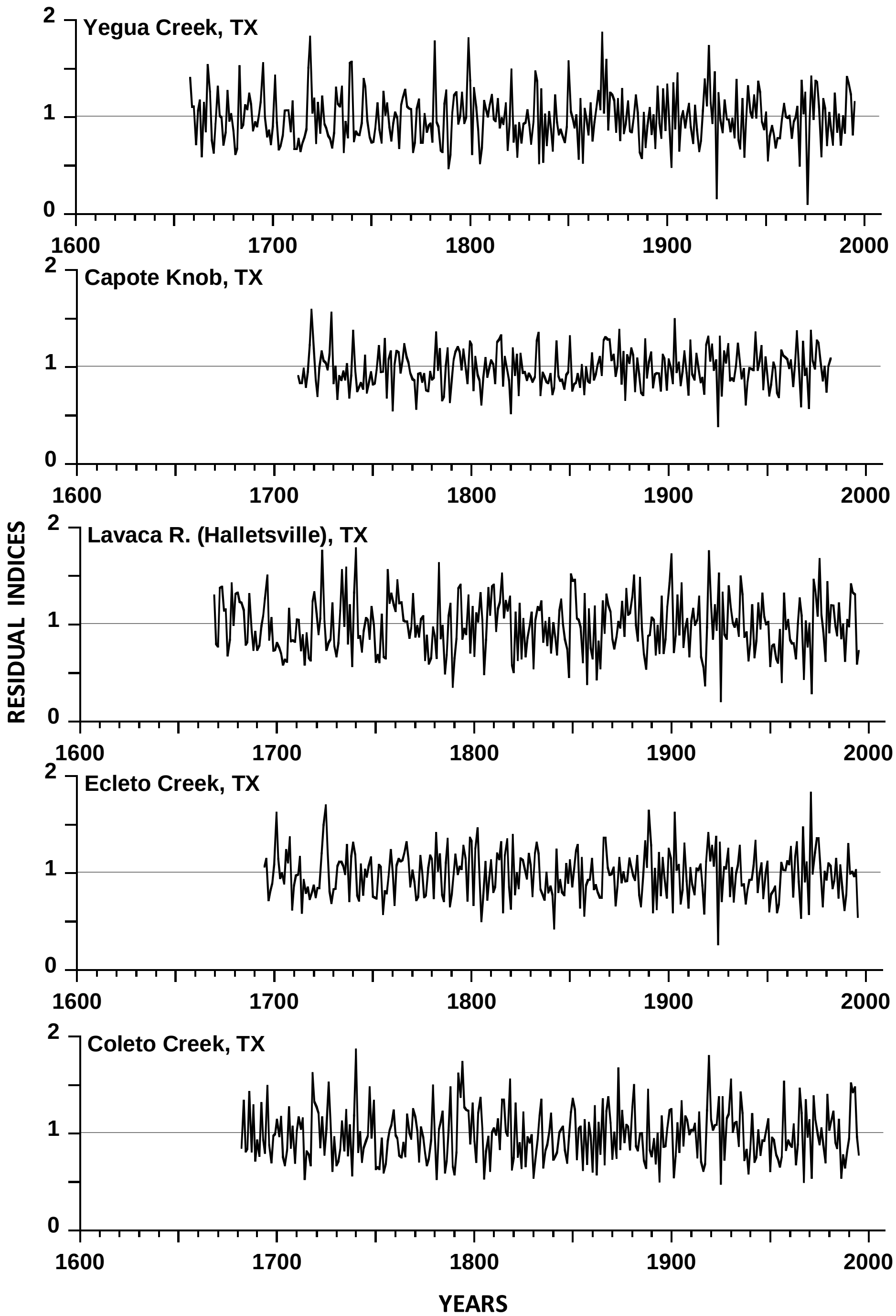

LBJ National Grassland, TX
Fort Wolters Savannah, TX
Fort Wolters Rocky Slope, TX
Kristas Canyon, TX
Palo Pinto Wilderness, TX
RESIDUAL INDICES
YEARS
0
1
2
1600
1700
1800
1900
2000


Little Maries River, MO
Pomme de Terre River, MO
Hahatonka State Park, MO
Democrat Ridge, MO
White Ranch St. For., MO
RESIDUAL INDICES
YEARS
0
1
2
1600
1700
1800
1900
2000


Mill Mountain, MO
Clayton Ridge, MO
Roaring River, MO
Greasy Creek, MO
Lower Rock Creek, MO
RESIDUAL INDICES
YEARS
0
1
2
1600
1700
1800
1900
2000


Norfork Lake, AR
Buffalo Park Boundary, AR
Malcolm's Ridge, AR
Wedington Mountain, AR
Hemmed in Hollow, AR
RESIDUAL INDICES
YEARS
0
1
2
1600
1700
1800
1900
2000


Point Peter Mountain, AR
Old Growth Study, AR
Brazos River, TX
Mason Mountain TX
Red Rock Creek, TX
RESIDUAL INDICES
YEARS
0
1
2
1600
1700
1800
1900
2000


Yegua Creek, TX
Capote Knob, TX
Lavaca R. (Halletsville), TX
Ecleto Creek, TX
Coleto Creek, TX
RESIDUAL INDICES
YEARS
0
1
2
1600
1700
1800
1900
2000