AN ABSTRACT OF THE THESIS OF

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Title: Remote Sensing and Tree-ring Study of Forest Condition in Northeastern Kansas

Abstract Approved: James M. Mayo

Vegetation changes related to climatic events were studied using remotely-sensed datasets combined with climatic data and tree-ring core samples. The study site was a deciduous forest at Fort Leavenworth in northeastern Kansas. My study correlated tree-ring width with forest growth and climatic events. Monthly data for temperature, precipitation, and drought indices were obtained from the National Climatic Data Center (NCDC).

Oak trees (*Quercus* spp.) on an undisturbed forested ridge were sampled using an incremental borer. Ring widths were measured for the period from 1967 to 1996, cross-dated, and standardized to remove the age-related trend. The growth of tree-rings was synchronized with the year-to-year variation of climatic pattern. The narrowest rings were found in 1977, 1980 and 1988 with the negative drought (-0.98, -1.02 and –2.06) Palmer Drought Severity Index values. The mid-1980s were favorable years for the forest in the Fort Leavenworth area. Ring widths were significantly correlated with overall climatic events and highly correlated with positive values for PDSI. Temperature did not influence ring-growth of oak species in the study area. Tree-ring data were compared to Normalized Difference Vegetation Index values (NDVI) from the remotely-sensed Landsat TM images.

Changes in NDVI values were not in phase with the climatic patterns and ring width patterns. Narrow ring growth occurred in the drought year of 1988 when NDVI values were high. However, greater ring growth occurred in a normal year (1990) when the NDVI value decreased. Results showed that ring widths responded immediately to the climate change, but tree-leaf growth responses apparently lagged by one to two years.

REMOTE SENSING AND TREE-RING STUDY OF FOREST CONDITION IN NORTHEASTERN KANSAS

A Thesis Presented

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Preface

My thesis follows the style of Ecology.

Key words: dendroclimatology, tree-ring, *Quercus* spp., Remote sensing, NDVI, lag effect, drought, PDSI, Fort Leavenworth.

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INTRODUCTION

Remote Sensing

Various environmental factors affect the physiological processes and vegetative growth of individual trees or forest populations. Those factors include climatic elements, abiotic and biotic components, and anthropogenic factors (see the review in Kramer and Kozlowski 1979). Among these factors, climactic events influence vegetation growth uniformly over a large area. Annual climatic changes affect forest growth, and monitoring these changes is important for natural resources management. Effects of environmental factors on vegetative growth can be studied using laboratory methods, field studies, and remote sensing techniques. Global climate change and vegetation effects have been successfully studied by using remote sensing techniques for over 25 years. Since the first Landsat was launched in 1972 by NASA, many studies have documented environmental changes over time. Remote sensing techniques provide valuable information for observing vegetative changes because of their synoptic view, repetitive coverage, and multispectral data (Avery and Berlin 1992, Wilkie and Finn 1996, Aber 1997). Remote sensing techniques have been used to determine seasonal or long-term vegetative changes, effects of environmental stresses, and destruction by logging, grazing, fires, insects, and diseases.

Vegetation changes can be monitored by remotely-sensed data imagery because it can detect the health of plants using the multispectral dataset. Forest vegetation often suffers environmental stresses associated with moisture, temperature, nutrients, insects, and disease (Fritts 1967, Kramer and Kozlowski 1979, Salisbury and Ross 1992). When plants are stressed, their symptoms of stress have diagnostic spectral characteristics that can be observed on molecular and cellular, morphological, and community levels. Sensor systems and image-processing techniques have been applied to detect these characteristics. Moreover, the scanner has the ability to separate vegetation from the soil surface or other physical features.

Remote-sensing techniques that employ satellite multispectral data can detect, quantify, map, and monitor vegetation on local, regional, and global scales. The Landsat TM data imaging provides the necessary spatial and spectral resolution to examine relatively small forest parcels and to derive vegetation indices based on visible and infrared reflectivity of active leaves. This study employed the Landsat Thematic Mapper (TM) to monitor the forest response to climatic factors, because it has been proven to detect the changes accurately (Rock et al. 1993). Landsat imageries detect only leaf canopy characteristics but do not identify detailed growth of individual trees.

Dendroclimatology

In temperate regions, the age of trees can be determined by counting growth rings from the lower part of the stem. The growth ring is referred to as an annual increment of growth, or tree ring. Dendroclimatology is the science of reconstructing the past climatic patterns from tree-rings (Fritts 1976, Schweingruber 1989, Swetnam et al. 1985). Tree-ring analysis has proven to be a useful tool in forest growth and climate studies. The width of an increment represents the annual cycle of the spring growth (earlywood) and the later growing season growth (latewood). Comparing ring width among trees can establish the exact year of a particular environmental condition, because ring growth is affected by favorable or unfavorable climates (Fritts 1976).

Tree-rings can be studied from tree stumps, the ends of logs, the tops of posts, or from core samples obtained by the tree-boring method (Phipps and McGowan 1994). Among these methods, tree boring is the best application to study radial growth of a living tree. An increment borer can be used to collect the sample without harming the trees. Boring scars can be covered with wax to prevent insect attack or disease infections. The use of tree-ring data to reconstruct the past climate changes is well documented since dendroclimatology was established in 1894 by Andrew E. Douglass (Fritts 1976). The effects of climate on the tree growth can vary from season to season, and year to year, or show long-term changes, depending on climatic factors or the age of the trees. However, non-climatic variations of growth can also occur. Some of the dendrochronological techniques can minimize non-climatic factors. Standardization curves have been developed to minimize factors such as age variations, location of cross sections, competition, stand history, and the productivity of the sites (Fritts 1976, Cook et al. 1990).

My thesis research focused on the use of remotely-sensed datasets in combination with climatic data and landscape characteristics such as topography, drainage, and soils. The main purpose of the study was to analyze the relationship of forest growth and climatic factors through the use of remotely-sensed data. To better understand forest condition, ground-based studies were included, and forest growth and structure patterns were obtained from tree-ring data using a statistical model. Tree-ring analysis provided information on climatic changes, especially for years of abnormal precipitation, drought, and extreme temperatures, which were compared with remote sensing data to test the effect of climatic events on cambial growth and leaf growth in the forest.

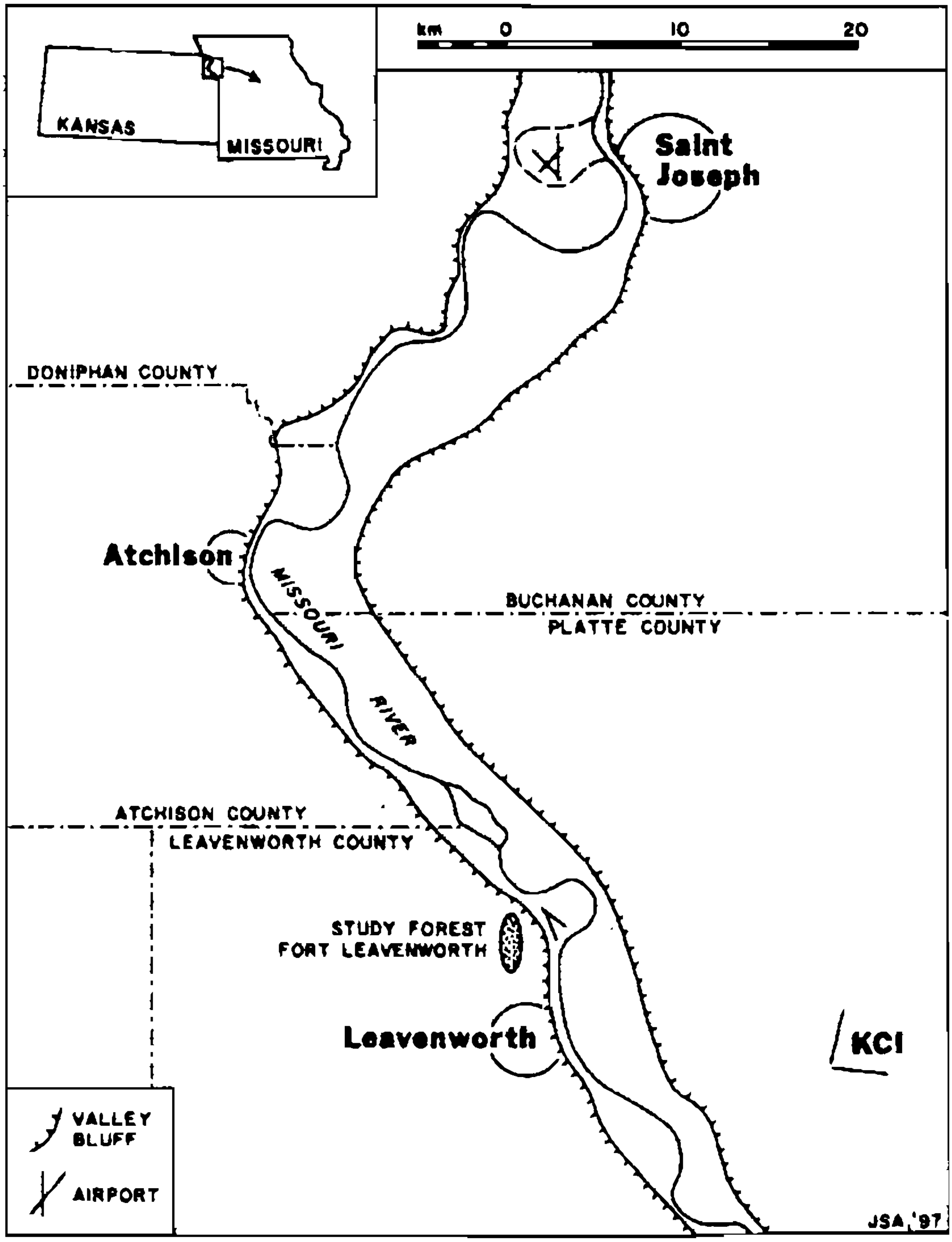
STUDY SITE DESCRIPTION

A preserved hardwood-forested area along the Missouri River Valley at Fort Leavenworth (Fig. 1) was chosen for the study site. Fort Leavenworth, the military reservation, is in the Leavenworth County, Kansas. This area is adjacent to and west of the Missouri River. Neighboring counties are Atchison, Jefferson, and Wyandotte. The study area is located between latitude N 39° 20' and N 39° 25' and longitude W 95° 00' and W 94° 55'. Tree samples were mostly taken from Sec. 11, 14, and 15, T. 8 S., R. 22 E. (Zavesky and Boatright 1977). The highest elevation in the county is about 1,100 ft. Because of the proximity to the Missouri River, Ft. Leavenworth areas have high moisture content. Thus, the area remains densely forested and preserved as a natural area, because of the presence of the Fort Leavenworth military reservation (Nowak unpublished data).

FOREST AREA (OAK-HICKORY FOREST)

Generally, Leavenworth County has fertile soils and favorable weather, both of which are suitable for forest growth. This area has three major forest ecosystems: the old forest, the new attrition land, and the area between the old forest and the main levee. The old forest is considered an undisturbed area, and the maximum age of the trees from this forest is estimated at 150 to 200 years. The new attrition land, which is located north of the tail levee, was a mud flat without trees in 1946. Since then, a new-growth forest was established in this area; some cottonwoods now being harvested have a diameter of 50 - 70 cm (Nowak unpublished data). The third area, between the old forest and the main levee was clear-cut in the 1960s, and several floods have occurred since then.

FIG. 1. Index Map for northeastern Kansas and northwestern Missouri showing location of the study forest at Fort Leavenworth military reservation and neighboring areas. Kansas City International Airport (KCI) can be seen in the map.



KANSAS
MISSOURI
km 0 10 20
Saint Joseph
DONIPHAN COUNTY
Atchison
MISSOURI RIVER
BUCHANAN COUNTY
PLATTE COUNTY
ATCHISON COUNTY
LEAVENWORTH COUNTY
STUDY FOREST
FORT LEAVENWORTH
Leavenworth
KCI
VALLEY BLUFF
AIRPORT
JSA '97

Only younger trees and grasslands occupy this area. Several oak species, hickory, and walnut are the dominant species in this forest (Table 1). Trees were chosen from the old forest because it is undisturbed and is located on the upland ridges where periodic stresses might have influenced growth.

SOIL DESCRIPTIONS

The areas selected for my research are well-drained on uplands soils with steep slopes. The soils from the Leavenworth County are fertile and suitable for wood production (Zavesky and Boatright 1977); thus, this area is mostly covered with dense forests. Soil series from my study sites and their related suitability tree species are shown in the Table 2. The potentials of wood productivity of the soils are given in groups 4o1, 4r2, and 5d2. The first numbers of the groups, 4 and 5, indicate moderate and low productivity, respectively. The second letter indicates the limitations of wood productivity. The limitation of "o" is the restriction for the usage of trees, "r" is the steep slopes, and "d" is the rooting depth where there are shallow rocks and shale. The last number indicates the degree of hazards or limitation; 1 shows no or slight limitations, and 2 indicates one or more moderate limitations. According to the group categories, wood production in the study area has low or moderate potential with few limitations.

CLIMATIC CONDITION

Climatic events are important for the vegetation growth in the forest because they influence the area uniformly. Northeastern Kansas has a typical continental climate (Zavesky and Boatright 1977). Weather changes within a short period are common.

TABLE 1. Tree species from the study areas (Data from preliminary investigation) (Stephens 1969, Nowak, unpublished data).

Common names	Scientific names	Location
Ash	*Fraxinus americana* L.	I, III
Box Elder	*Acer negundo* L.	I, II
Buckbrush	*Symphoricarpos orbiculatus* Moench	I
Cottonwood	*Populus deltoides* Marsh.	I, II, III
Hickory	*Carya* spp.	I
Honey Locust	*Gleditsia triacanthos* L.	III
Hackberry	*Celtis occidentalis* L.	I
Oak	*Quercus* spp.	I
Pawpaw	*Asimina triloba* (L.) Dunal	I
Pecan	*Carya illinoensis* (Wang.) K. Koch	I, III
Silver maple	*Acer saccharinum* L.	I, II
Sycamore	*Platanus occidentalis* L.	I, II
Walnut	*Juglans nigra* L.	I

I = The old forest

II = The new attrition land

III = The area between the old forest and the main levee

TABLE. 2. Soil types from the study areas (T. 8 S, R. 22 E) and the tree species (Data compiled from the Zavesky and Boatright (1977).

Sections	Soil series	Slope	Group	Most common tree species
11	Knox Complex (Kn)	18 - 30%	4r2	White Oak, Black Oak, Shagbark Hickory
11, 14, 15	Gosport-Sogn Complex (Gs)	7 - 35%	5d2	White Oak, Black Oak, Black Walnut
11	Gosport Complex (Gc)	10 - 30%	5d2	Oak, Hickory, Walnut
11, 14, 15	Ladoga Silt Loam (La)	4 - 7%	4o1	White Oak, Black Oak, Red Oak, Black Walnut, American Basswood

The annual temperature in this area has a wide range of minimum and maximum temperatures. Minimum average temperature was 11.7 °F (-11.3 °C) and the maximum average temperature was 85.1°F (29.5 °C) in thirty years. Two years in 10 have approximately four days with the minimum temperature – 8 °F (-22.2 °C) and maximum temperature 101°F (38.3 °C) (Zavesky and Boatright 1997).

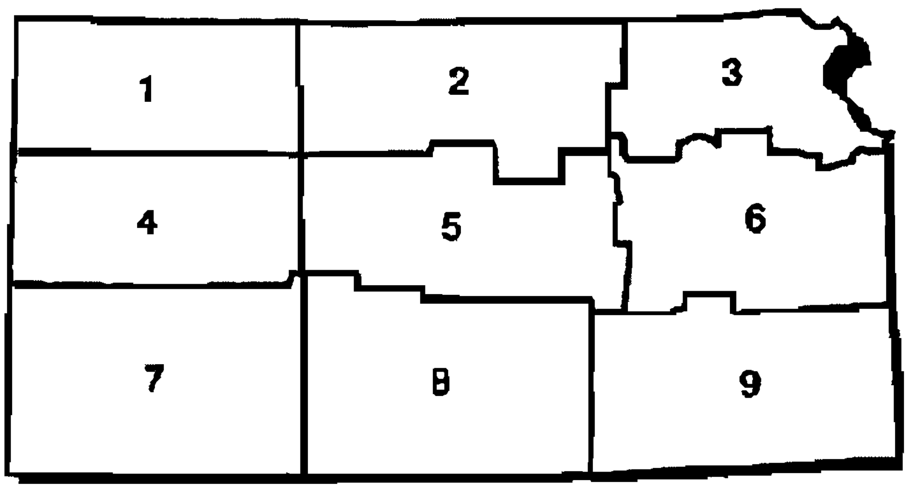
During the study period from 1967 to 1997, there were no anomalous temperature changes recorded. The average temperature for the study period was 11.7 °C and the average precipitation was 924 mm. The average annual precipitation in the area is about 900 mm and about 70% of the annual rainfall occurs during the growing season, from April through September. Monthly data for temperature, precipitation, and drought indices were acquired for Kansas Division 3 from National Climatic Data Center (NDCD) (Fig. 2). Climatic data for Kansas Division 3 were chosen because they represent the regional scale climatic trend for the study area.

MATERIALS AND METHODS

LANDSAT THEMATIC MAPPER DATASET

Spring, summer, and autumn imagery of selected years were used for analyzing rural resources, with a special emphasis on identifying vegetation changes related to climatic events. However, cloud-free images were not available from Landsat TM data for some wet spring and early summer periods. Because of the lack of cloud-free images for the spring and early summer in many years, the project focused on three-season imagery from 1988 and 1994 and summer imagery from 1987 and 1990 for interannual comparisons of forest conditions. Overall forest canopy response to climatic events as

FIG. 2. Kansas Division 3. Climatic data are available online from National Climatic Data Center (NCDC). Fort Leavenworth is located in Kansas Division 3.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studied for four years with July imagery; however, wood growth responses during cloud-cover periods could not be obtained from the remotely-sensed dataset. Therefore, ground-based observations were added to the project to provide information on forest composition and structure of the ground condition. Ground observation included the study of wood growth responses. Kite aerial photography was also used for general study.

Wood growth responses can be measured by radial growth, which requires detailed analysis of tree-ring widths (Swetnam et al. 1985). The results from the growth observation were compared with the landsat dataset. The project acquired Landsat TM datasets, path 27, row 33, from the EROS Data Center, U.S. Geological Survey in Sioux Falls, South Dakota, and Kansas Applied Remote Sensing Center in Lawrence. Datasets from 1987, 1988, 1990, 1994, and 1997 were acquired for spring, summer and autumn imageries (Table 3). However, because of cloud-cover seasons in spring and early summer, only 20% of complete, cloud-free data from northeastern Kansas could be obtained. In particular, images for the flood year of 1993 were incomplete because of cloud cover; thus the after-flood year of 1994 was selected as an alternative year. July data were available for all of the studied years. In total, three-season imagery (spring, summer, and autumn) for 1988 and 1994 were analyzed. For maximum forest activity, summer (July) images from 1987 and 1990 were also analyzed. A total of eight images were studied for the project.

The collected images were processed by Wilkins (1997) as a part of the entire study project. Idrisi software (1995) was used to analyze the images. The ground coordinates from the study area were obtained with Differential Global Position System

(DGPS) (Table 4). Those ground coordinates were used to resample sites corresponding to the remote sensing images. Ft. Leavenworth is located in the Universal Transverse Mercator Projection (UTM) zone 15. A Normalized Difference Vegetation Index (NDVI), which measures the active green-leaf area (Tucker 1979), was derived from the resampled images. NDVI values were used to characterize as the forest canopy growth.

TREE-RING METHODS

Sample Collection

This study used tree-boring methods to study the condition of living trees. Tree-ring records were collected and analyzed to support a full spectrum of samples from satellite data and climatic records. Identification of trees, forest structure, and core-sample drilling for tree-ring study were employed to study the relationship between forest growth and climatic factors. Samples were taken from the area within the Kansas Division 3 climatic area where long-term meteorological records are maintained. I collected data from the undisturbed forest at the upland ridges because they would be expected to suffer water stress more than the trees from the wetland areas (Fritts 1976, Schweingruber et al. 1990).

Trees were randomly chosen, but I selected only trees without injuries or any uncommon appearance. The target portions of the rings were the outer regions, close to the cambium; thus only unblemished trees were chosen. The exact location for each tree was recorded along with prominent features or with the nearest UTM coordinates (Fig. 3). Drainage condition, slope, and foliage for each tree were recorded (Table 5). The study areas were mostly on the Knox complex, Gosport complex, Gosport-Sogn complex,

TABLE 3. Suitable LANDSAT Imagery for Leavenworth County, Kansas, 1987-96

Landsat path 027, row 033.

Year	Scene ID
July 23, 1987	LT5027033008720410
June 7, 1988	LT5027033008815910
July 25, 1988	LT5027033008820710
October 13, 1988	LT5027033008828710
July 15, 1990	LT5027033009019610
May 23, 1994	LT5027033009414310
July 10, 1994	LT5027033009419110
September 28, 1994	LT5027033009427110

TABLE 4. Actual ground coordinates by DGPS for Ft. Leavenworth (UTM zone 15).

No.	Site Description	East - km	North - km
1	Southeast corner of parking lot in skeet shooting area	0332.840	4357.995
2	Southwest corner large storage building parking area	0332.758	4358.725
3	North east corner of water tower	0332.746	4357.513
4	Airport runway, center of south end	0335.355	4358.549
5	Airport runway, center of north end	0334.762	4360.249
6	Service area east of airport, northwest corner parking lot	0335.820	4359.953
7	Northwest corner of Coffin and 155th Road	0333.051	4360.251
8	Two circular tanks, east side of ridge top	0333.293	4359.133
9	Southeast corner Warehouse Road	0334.880	4355.844
10	Federal prison, southeast corner parking lot	0333.373	4355.055

FIG. 3. Map of the sampled trees. Oak tree samples were taken from the Ft. Leavenworth along the upland ridges. The exact places for tree samples were shown with sample numbers. Locations for each sample were recorded for future resample.

* - Sampled Trees

▲ - DGPS ground coordinates location

○- Water Tank

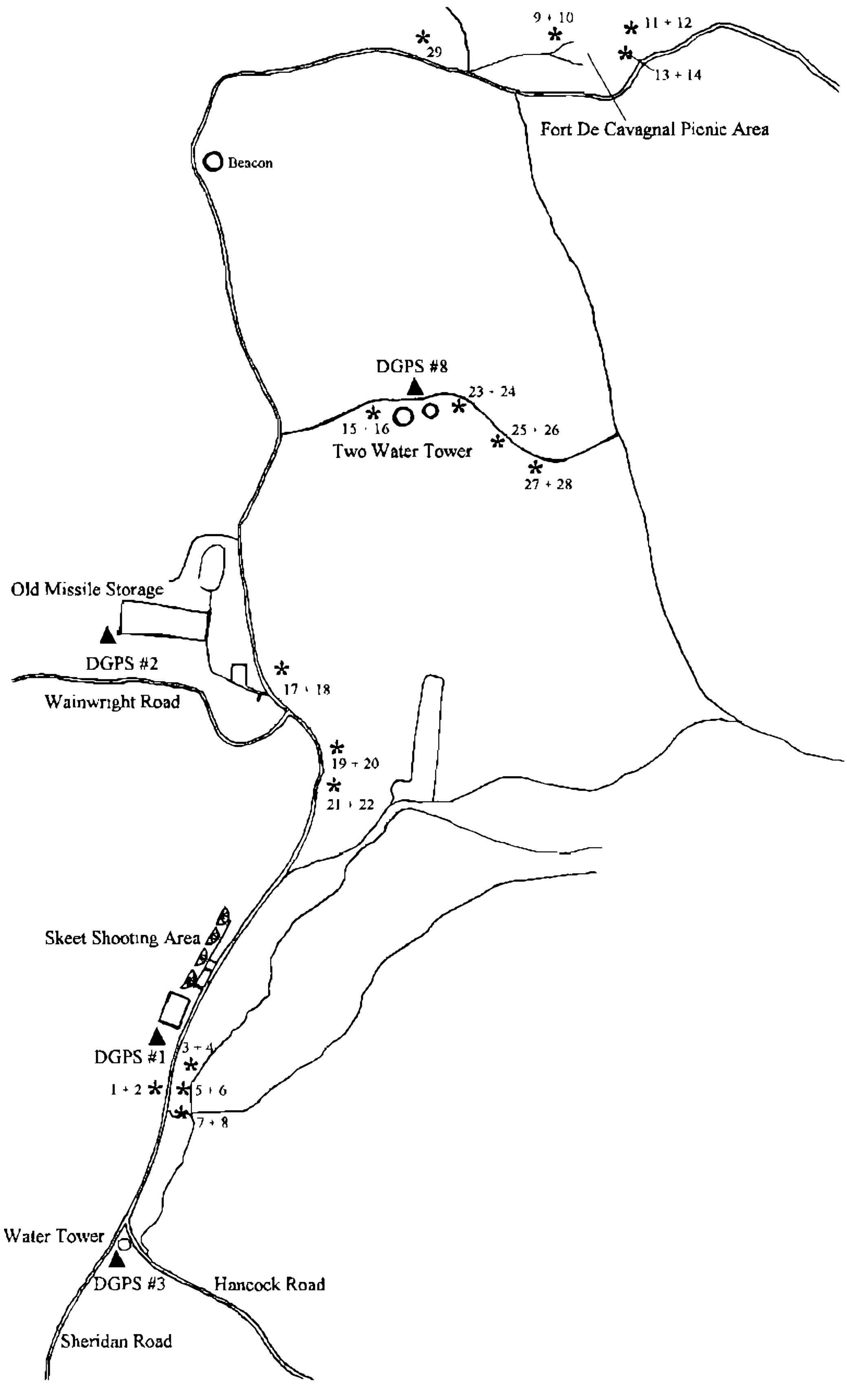
9 + 10
11 + 12
29
13 + 14
Fort De Cavagnal Picnic Area
Beacon
DGPS #8
23 + 24
15 + 16
25 + 26
Two Water Tower
27 + 28
Old Missile Storage
DGPS #2
17 + 18
Wainwright Road
19 + 20
21 + 22
Skeet Shooting Area
DGPS #1
3 + 4
1 + 2
5 + 6
7 + 8
Water Tower
DGPS #3
Hancock Road
Sheridan Road

TABLE 5. Recorded information for slopes and their aspects, drainage condition and location for each tree.

No.	Slope	Aspect	Drainage	Location
001 & 002	Moderate	South	Very good	50 m south of shooting area along the road
003 & 004	Moderate	South	Very good	50 m south of shooting area along the road
005 & 006	Moderate	South	Very good	50 m south of shooting area along the road
007 & 008	Moderate	South	Very good	50 m south of shooting area along the road
009 & 010	Steep 20°	North	Very good	Fort De Cavagnal Picnic area (entrance)
011 & 012	Steep 20°	North	Very good	Fort De Cavagnal Picnic area (East)
013 & 014	Steep 20°	North	Very good	Fort De Cavagnal Picnic area (East)
015 & 016	Gentle	North	Good	East of the two water tanks
017 & 018	Moderate	East	Good	100 m north from Wainwright Road
019 & 020	Gentle	East	Good	50 m east from Wainwright Road junction
021 & 022	Gentle	East	Very good	60 m east from Wainwright Road junction
023 & 024	Moderate	North	Very good	North of two water tanks
025 & 026	Moderate	North	Very good	20 m south of two tanks on the trail road
027 & 028	Gentle	North	Good	30 m south of two tanks on the trail road
029	Gentle	East	Very good	200 m west of picnic area, on Sheridan Road

and Ladoga Silt Loam soils series; all have a moderate potential for wood production (Zavesky and Boatright 1977). The condition and the environment of each tree were recorded in detailed as recommended by Schweingruber et al. (1990). Detailed records are important for tree-ring studies because specific trees are to be resampled in the future, and they must be relocated (Fritts 1976). Samples were taken over four different directions, which were determined by compass, in three days.

Core samples were taken by incremental borer from different directions (east, west, north and south) of the stem to minimize the differences of stem growth. Samplings were done in two days in late spring (May) and one day in autumn (September) (Table 6). Detailed records of each sampled tree are shown in Table 7. Various oaks (*Quercus* spp.) were chosen because they are weather-sensitive but not overly reactive to climate. Extremely sensitive and non-sensitive trees are not recommended for obtaining tree-ring samples to study dendroclimatology (Fritts 1976). The samples were collected from the same site because tree growth depends on the same limiting factors. Samples were taken from 15 trees, a minimum of five to seven trees was recommended by Schweingruber et al. (1990). Wood samples were collected at breast height as recommended by Fritts (1976), Swetnam et al. (1985), and Schweingruber et al. (1990) using a 17-inch Swedish incremental borer.

On May 22 and 23, 1997, the first groups of samples were taken from three chestnut oaks (*Quercus muehlenbergii* Engelm.), two red oaks (*Quercus rubra* L.), and one each from black oak (*Quercus velutina* Lam.), post oak (*Quercus stellata* Wang) and white oak (*Quercus alba* L.). After processing the samples, the annual rings from the chestnut oaks were found to be indistinct and difficult to measure. Therefore, chestnut

TABLE 6. Date of samples taken and the direction of the core samples from each tree.

No.	Common Name	Date	Directions
001	Red Oak	May 22, 1997	East to West
002	Red Oak		South to North
003	Black Oak		East to West
004	Black Oak		North to South
005	Post Oak		South to North
006	Post Oak		West to East
007	Red Oak		North to South
008	Red Oak		West to East
009	Chestnut Oak	May 23, 1997	East to West
010	Chestnut Oak		South to North
011	Chestnut Oak		East to West
012	Chestnut Oak		North to South
013	Chestnut Oak		North to South
014	Chestnut Oak		East to West
015	White Oak		North to South
016	White Oak		West to East
017	Black Oak	September 28, 1997	North to South
018	Black Oak		East to West
019	Black Oak		West to East
020	Black Oak		North to South

TABLE 6. Date of samples taken and the direction of the core samples from each tree.

(Cont.)

No.	Common Name	Date	Directions
021	Black Oak	September 28, 1997	East to West
022	Black Oak		North to South
023	Black Oak		North to South
024	Black Oak		West to East
025	Red Oak		North to South
026	Red Oak		West to East
027	Black Oak		South to North
028	Black Oak		West to East
029	White Oak		South to North

TABLE 7. Tree descriptions from tree-boring samples.

No.	Height ≈	Circumference	Foliage Density	Trunk Condition
001 & 002	25 m	236 cm	Medium	Excellent, no fault
003 & 004	25 m	130 cm	Heavy	Excellent, faultless to 20 m
005 & 006	20 m	164 cm	Weak	Good, faultless to 5-10 m
007 & 008	23 m	150 cm	Heavy	Excellent, no fault
009 & 010	20 m	114 cm	Heavy	Excellent, no fault, Slope (North side of the ridge)
011 & 012	26 m	145 cm	Heavy	Excellent, no fault, Slope (North side of the ridge)
013 & 014	24 m	109 cm	Medium	Excellent, no fault, Slope (North side of the ridge)
015 & 016	23 m	142 cm	Heavy	Excellent, no fault
017 & 018	18 m	130 cm	Heavy	Excellent, no fault
019 & 020	20 m	168 cm	Medium	Excellent, no fault
021 & 022	20 m	188 cm	Heavy	Excellent, no fault, slightly southward slant
023 & 024	24 m	208 cm	Medium	Excellent no fault
025 & 026	15 m	168 cm	Medium	Excellent, no fault
027 & 028	15 m	147 cm	Heavy	Excellent, no fault
029	20 m	206 cm	Heavy	Excellent, no fault

oak was not included in future sampling. Samples must have a distinct, growth-layer boundary to distinguish the rings (Fritts, 1976). During the second sampling period, on September 28, 1997, five black oaks, and one each of red oak and white oak were selected. Two core samples from each tree were bored diagonally in north, south, east, and west directions, which were determined by using a compass (Table 5). Tree number 15 had only one core sample taken because the instrument failed to extract descent core sample. Thus, a total of 29 samples from 15 trees were taken from the study area.

Sample Preparation and Measuring

Collected core samples were dried and surface polished for examination. Surface polishing was performed using the series of sandpaper (Schweingruber 1989). I used sandpaper series 100 for coarse polishing and 220 for fine polishing. After polishing the samples, ring widths were examined by ring-width measurement equipment: Bengan Mod. V. Ser. II. Sweden. This instrument has an accuracy of 0.1 mm. I measured each specimen at least twice, and calculated an error term from the difference. Samples were measured for thirty rings, which represented the calendar years from 1967 to 1996. The tree-ring laboratory of the U.S. Geological Survey recommends that the specimens should be remeasured if the standard deviation is greater than 0.1 mm. Ring widths were measured until the absolute difference became 0.05 mm among the measurements. Inconsistent measurements were remeasured by a second person (Fritts 1976). Ring sample number 018 did not have enough rings for thirty years of study. This sample had obviously wider ring and indicated that it was from a younger tree. Thus, ring sample 018 was eliminated from the data.

Crossdating – Skeleton Plotting

Although the last year for all samples taken was known, crossdating was applied to detect false rings and missing rings. Crossdating can identify the year in which each ring was formed and assign exact calendar dates to the rings (Fritts 1976). False rings can be detected by microscopic examination of cells within rings, but a missing ring can be detected only by crossdating that compares samples from each site and between different sites. Because of the sensitivity of the trees, I used a skeleton plotting method for crossdating. If the tree does not respond strongly to the climate, the skeleton plotting method is preferred (Cleaveland 1979). The skeleton plots (Swetnam et al. 1985) are shown in Fig. 4. Skeleton plotting was done on the graph paper. The width of each ring was compared with its neighboring rings. If the width was not much different from the neighboring rings, no marked was drawn. However, if the width was obviously narrower than the neighboring rings, one strike was marked. The narrower the ring width, the longer strike was marked on the graph paper. The patterns of the plots were compared with another sample from the same tree, as well as within the sample cores.

After crossdating the rings, the sample numbers 017, 027, and 028 were found to have anomalous values because of the young ages of the trees. They were difficult to crossdate with other rings, and were eliminated from the statistical analysis. Fritts (1976) also suggested that the first few decades of vigorous growth be discarded because the records from these widths did not accurately reflect the climate. Thus, a total of 25 samples were analyzed. Because my study period was only thirty years, the possibilities of finding missing rings or false rings were rare and none were found from the samples. Pilcher and Baillie (1980) also found that missing rings and false rings are rare in oak species. The plots showed that all rings that represented the calendar year 1988 were obviously narrow. Therefore, I assumed that the measurements for the samples were matched with their calendar years.

CLIMATIC DATA

The responses of tree growth also vary locally. Therefore, it is necessary to know the detailed response to the local climate. A block of climate data for 30 years or more is called macroclimate, and such a block is more stable and averages the frequent occurrence of different climate changes (Kozlowski 1971). Hence, in this study, climatic data were obtained from 1967 to 1996, for the particular area. The Landsat dataset was also available for this period. During the study period, 1977, 1980, and 1988-89 were very dry years, whereas 1973, mid-1980(s), and 1993 were relatively good years for northeastern Kansas. Climatic data are maintained the local stations, and at the NDCD. Fritts (1976) suggested that the climatic data should be obtained from weather stations where long-term data are maintained for a numbers of years. Leavenworth, and neighboring stations—Atchinson, St. Joseph, and Kansas City— did not have complete monthly climatic data for thirty years.

Climatic data are available online from the NCDC and include climatic division drought data for the period from 1895 to the present. Data files are updated data monthly. Data from 1967 to 1997 were downloaded from NCDC. I acquired "Time-biased Corrected" monthly average temperature (to 0.1°F) and precipitation (to 0.01 in.), and Palmer Drought Indices (PDSI, PHDI, PMDI, and ZNDX) (Palmer 1965). PDSI, PHDI, ZNDX, and PMDI are abbreviated from Palmer Drought Severity Index, Palmer

FIG. 4. Skeleton Plottings. This procedure follows Swetnam et al. (1985). Graph paper was used to draw skeleton plots. Years of the rings were marked on the paper. Ring-widths were compared with their neighboring rings. If the ring was narrower than neighboring rings, I marked one stroke on the graph paper. Depending on the degree of width, the length of the stroke was marked. The longest mark indicated the narrowest ring among the samples. Then, each sample was compared to others. Missing rings and false rings could be detected by this method, but neither missing rings nor false rings were found.

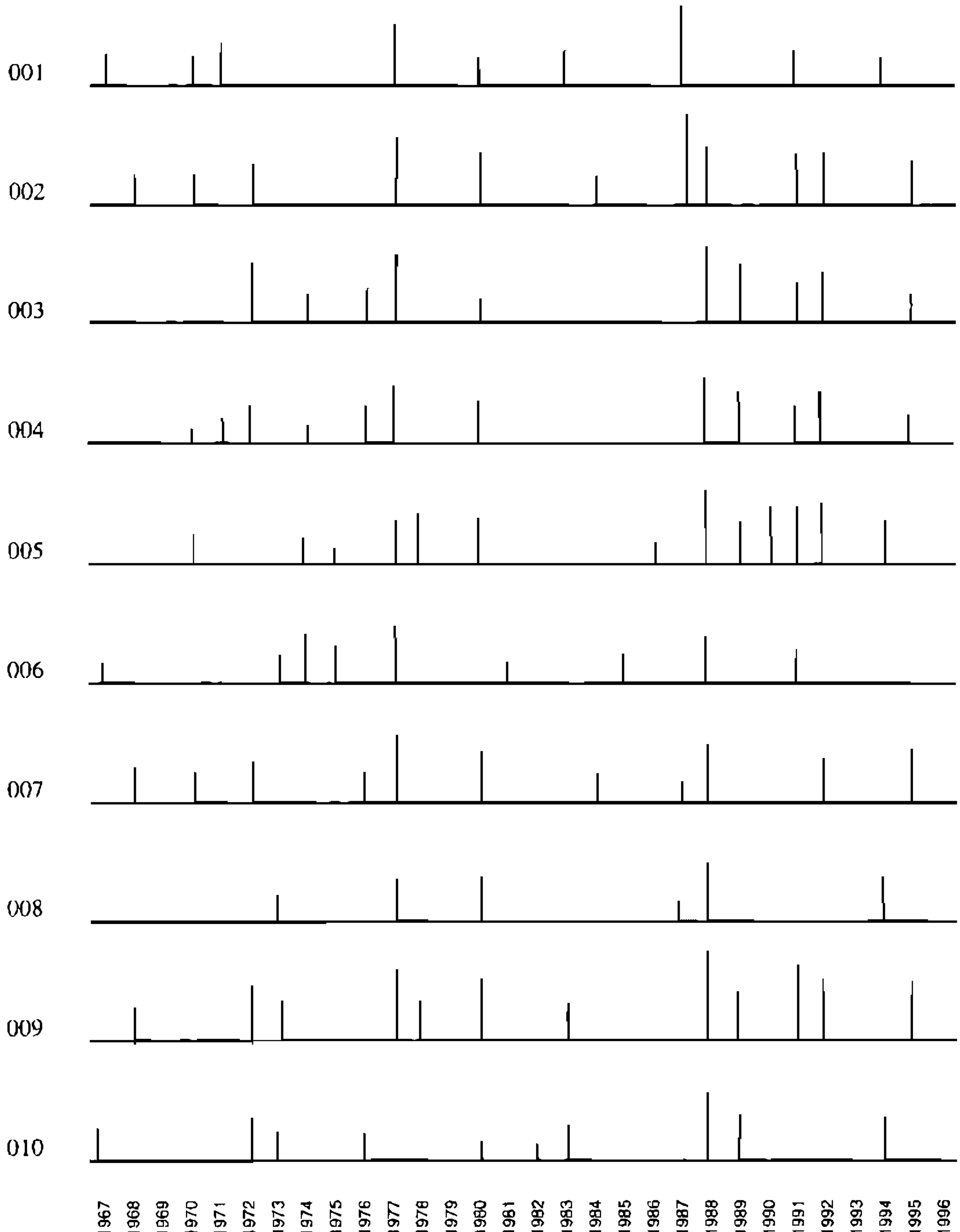
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Fig. 4. Skeleton Plottings (Cont.)

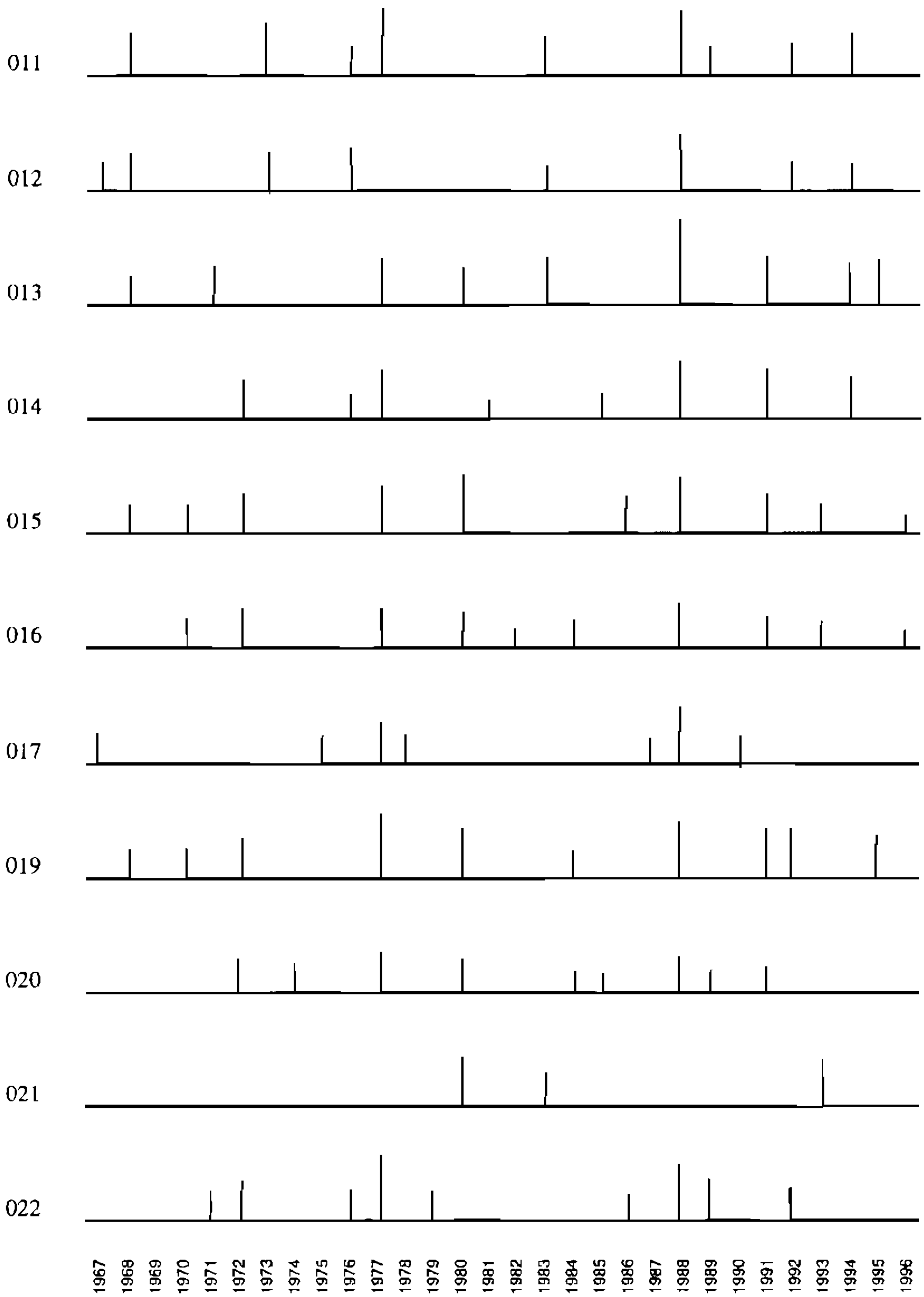
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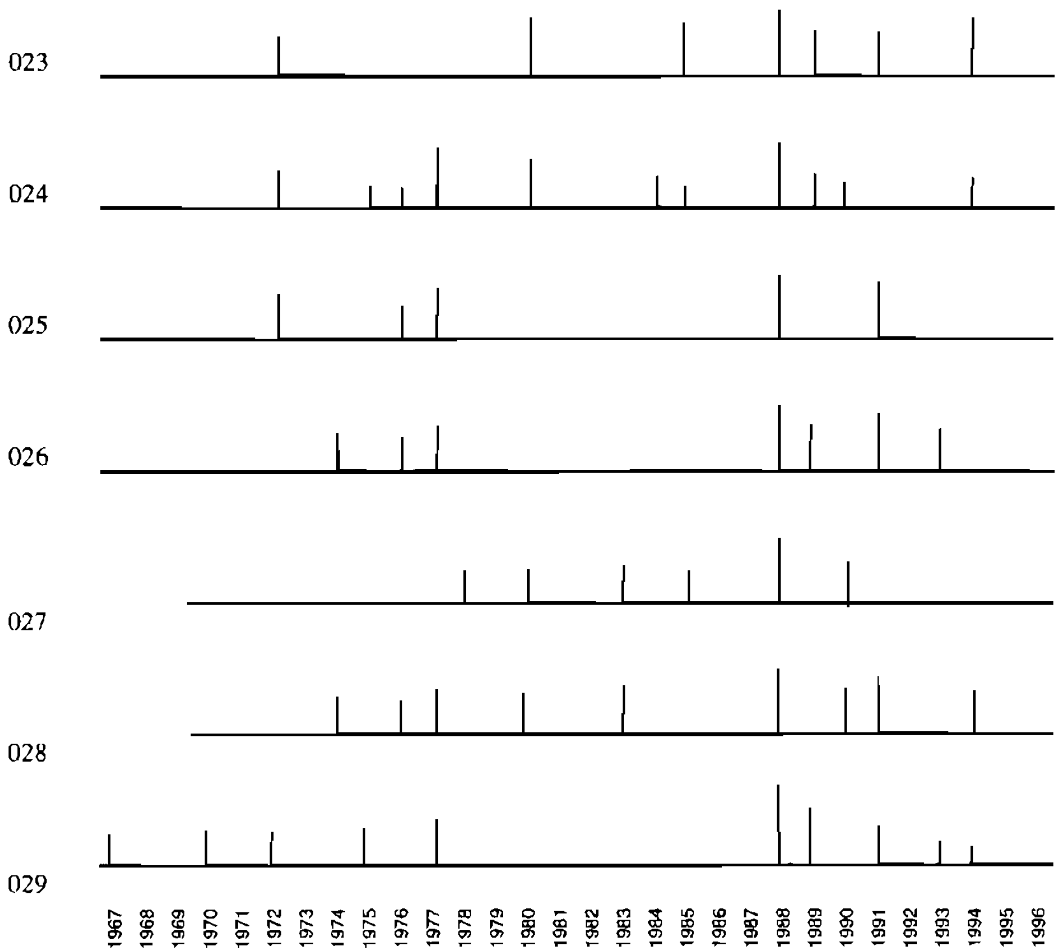
Fig. 4. Skeleton Plottings (Cont.)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1996

Hydrological Drought Index, Palmer "Z" Index, and Modified Palmer Drought Severity Index respectively.

PDSI is the monthly meteorological drought index used to assess the severity of dry or wet periods. PHDI is a hydrological drought index used to assess long-term moisture supply. Drought indices are the monthly values (index) generated monthly that indicates the severity of wet or dry periods (Table 8). They are based on the principle of a balance between moisture supply and demand. Man-made changes to the moisture supply are included in the computation of the indices. The indices generally range from -6 to +6, with negative values denoting dry climate, and positive values indicating wet climate. There are few values in the magnitude of +7 or -7.

ZNDX can be expressed as the "Moisture Anomaly Index". Each monthly Z value is a measure of the departure from normal of the moisture climate for that month. This index responds to a month of above-normal precipitation, even during periods of drought. ZNDX values vary from less than –2.75 to more than 3.50, where –2.75 is extreme drought and 3.50 is extreme wet. PMDI is a modification of the PDSI. The modification was made by the National Weather Service Climate Analysis Center for operational meteorological purposes. The modified PMDI incorporates a weighted average of the wet and dry index terms, using the probability as the weighting factor. The PMDI and PDSI have the same value during an established drought or wet spell (i.e., when the probability is 100%), but they have different values during transition periods.

TABLE 8. PDSI, PHDI values and their indicators.

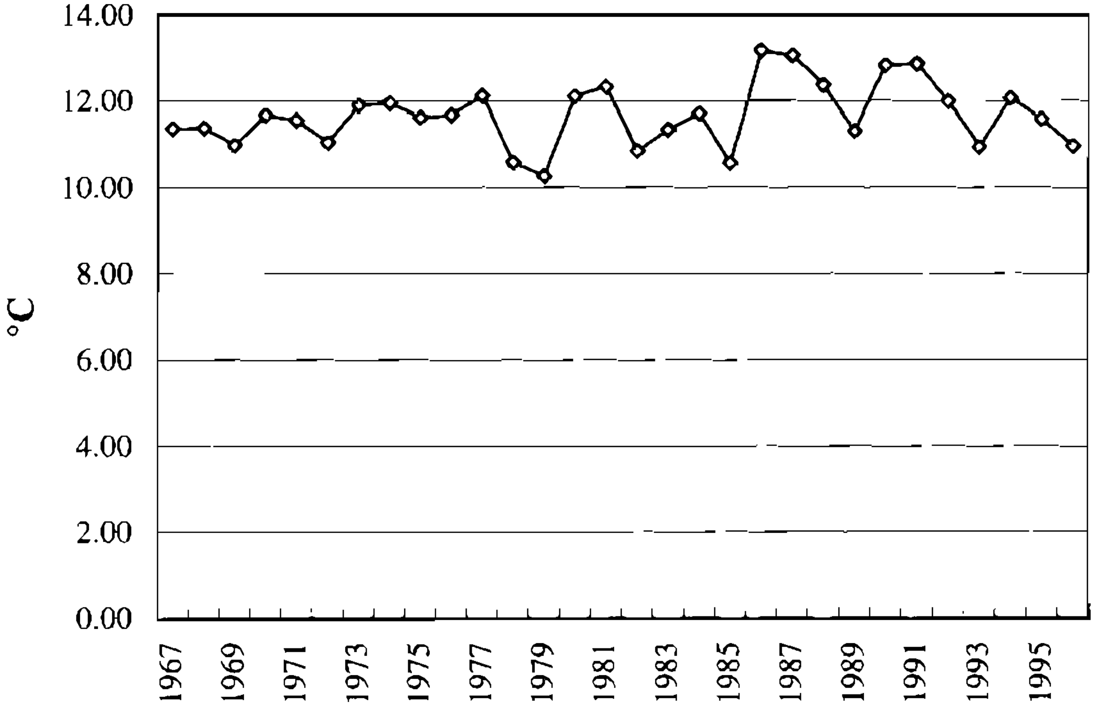
Indices	Condition
Greater than 4.0	Extreme wet
3.0 to 4.0	Severe wet
2.0 to 3.0	Moderate wet
1.0 to 2.0	Mild wet
0.5 to 1.0	Incipient wet
0 to ±0.5	Normal
-0.5 to -1.0	Incipient drought
-1.0 to -2.0	Mild drought
-2.0 to -3.0	Moderate drought
-3.0 to -4.0	Severe drought
less than - 4.0	Extreme drought

TREE-RING ANALYSIS

I analyzed data using SAS (SAS 1986). Measurements of ring-width from each sample were averaged to minimize the effects of non-climatic factors (Appendix A). Climatic data were obtained from a monthly average dataset. I calculated annual means for temperature, precipitation, PDSI, PHDI, ZNDX and PMDI. The annual climatic data are shown in Appendix B. The variations of temperature, precipitation, and the drought indices from 1967 to 1996 are shown in figures 5, 6 and 7. The Pearson Correlation Coefficient was used to find a correlation between tree-ring growth and the climatic events. Average ring widths were plotted against the calendar year to obtain year-to-year variation (Fig. 8). Data showed a slightly negative trend because as trees grow older, the widths of the rings become smaller. The growth trend or age-related trend was then removed from the model. Removing the age-related trend was expected to minimize the fluctuations caused by age factor and to adjust the growth reflected by the climatic factors. Standardization method (Fritts 1976, Warren 1980) corrected the age trend by using best-fit regression line.

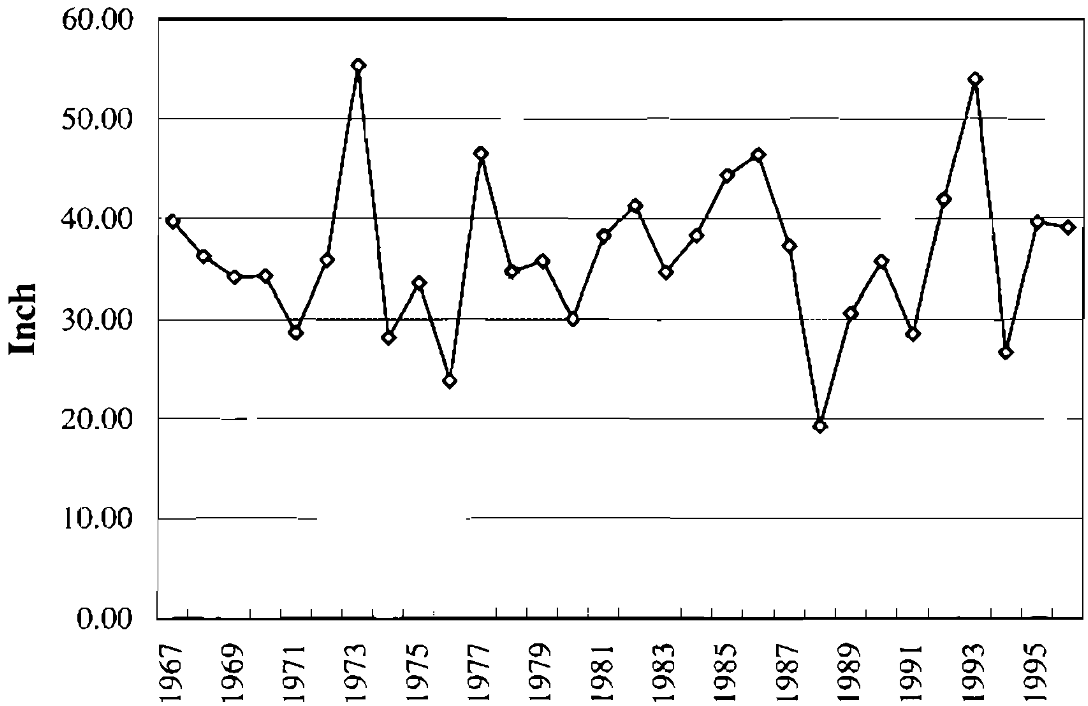
Residual values were derived from the regression model (Appendix A). Residual values are the plus and minus values that deviate from the mean trend. The Pearson Correlation Coefficient was used again to correlate the age-corrected residual values and climatic parameters. Co-linearity was detected among the climatic variables because they were derived from the same parameter source. Therefore, the best variable for the model from the climatic parameters was determined from a stepwise regression.

FIG. 5. Variation of temperature from 1967 to 1996. Temperature was not highly fluctuated during those periods. The average monthly minimum temperature and maximum temperature within thirty years were 10.3 °C and 13.2 °C, respectively.



14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
°C
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995

FIG. 6. Variation of annual precipitation from 1967 to 1996. During thirty years, 1973 and 1993 were recorded the maximum rainfall and 1980, and 1988 were the drought years. In generally, mid-1980s had the above average rainfall. The highest and lowest rainfall within thirty years were 55.4 mm and 19.2 mm respectively.



60.00
50.00
40.00
30.00
20.00
10.00
0.00
Inch
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995

FIG. 7. The variation of drought indices from 1967 to 1996. Drought indices are monthly values, which indicates the severity of wet or dry periods. The indices are range from +6 to –6, where plus sign indicates moisture supply and minus sign indicates moisture demand.

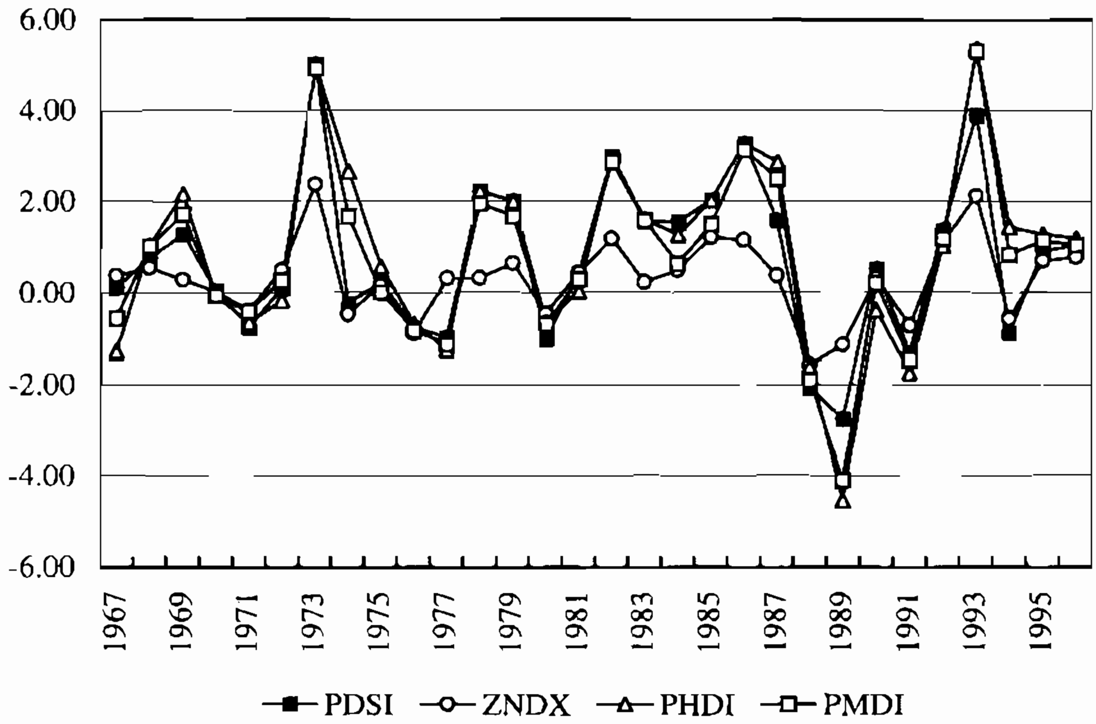
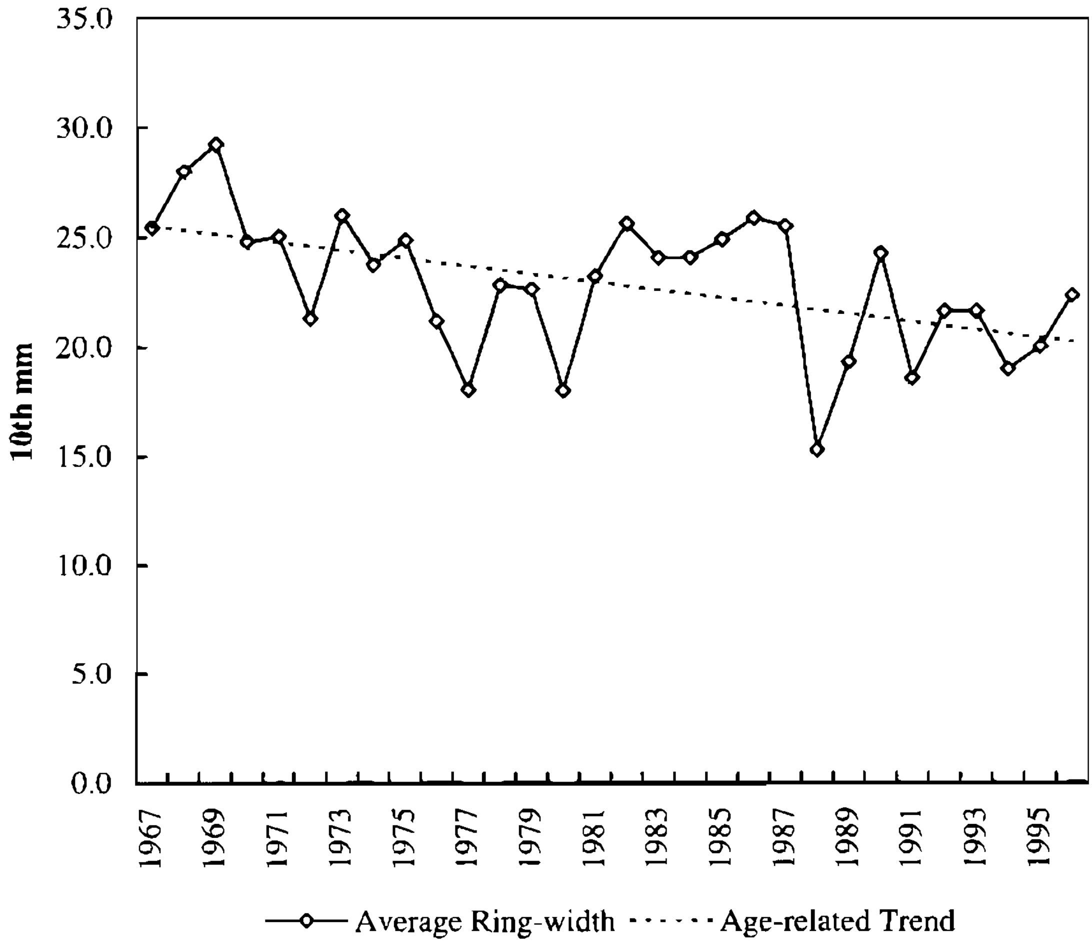

6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
PDSI
ZNDX
PHDI
PMDI

FIG. 8. Average ring width of oak trees sample as plotted against calendar year. The variation of the ring growth synchronized with the climatic variation. The years 1977, 1980, and 1988 showed the lowest ring-widths. The mid-1980s were favorable years for tree growth. This graph showed the slight downward slope as the age increased. That negative slope was caused by the age-related trend.



35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
10th mm
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
Average Ring-width
Age-related Trend

RESULTS

Tree-ring

Average ring-width was correlated with each climatic parameter (Table 9) except temperature. The Pearson correlation coefficient R-value for temperature was not significantly correlated to the ring-widths and therefore temperature was removed from further analysis. Precipitation (PPT.), PDSI, PHDI, ZNDX, and PMDI were all significantly correlated with tree-ring width at different p levels. PDSI had the highest r-value (P = 0.001) and PPT has the lowest r-value (P = 0.05). The plot of average ring-width vs. calendar years showed the year-to year variation, which synchronized with the climatic pattern (Fig. 8). The drought years of 1977, 1980 and 1988 showed the narrowest ring widths. PDSI indices for these years had negative values of –0.89, -1.02, and –2.06, respectively. Precipitation was low for these years and was measured at 118.11 mm, 76.18 mm, and 48.82 mm respectively. The widest ring-width occurred in 1969. Ring-width decreased dramatically as the age of the trees increased. Thus, total ring-width growth had a negative slope. The regression line for ring width had a negative slope for the age-related factor (1) ($r^2 = 0.25$; d.f. = 29; $p<0.005$).

$$\text{Average ring width} = (-0.182 \times \text{Age}) + 25.693 \tag{1}$$

The standard regression model was used to adjust for the age-related factors from the analysis. Thus, the residual values were free from the age factor (Fig. 9). Residual values were derived from the simple linear regression model (Appendix A). The residual values, predicted values, and 95% confidence intervals for the mean ring-width are given in Fig. 10. The Pearson Correlation Coefficient for residual values and climatic parameters showed that r-values increased in the analysis with raw average ring-width

(Table 10). The correlation coefficient between PDSI and residual values was the highest among the climatic parameters. A stepwise regression suggested that, PDSI was the best predictor variable among the climatic parameters. This model produced the smallest error mean square ($r^2 = 0.45$; d.f. = 29; p = 0.00001). Using a multiple regression did not improve the model. Therefore, a simple linear regression model was selected PDSI as the predictor variable (2).

$$\text{Residual values} = (1.062 \times \text{PDSI}) - 0.776 \tag{2}$$

Landsat

The results from the tree-ring study were compared with the results from the remote sensing study (Fig. 11). From the remote sensing study, NDVI values were derived for vegetation growth (Wilkins 1997). As the NDVI values were derived from the same forest area, it was possible to study the wood and vegetation response to climatic variation. NDVI values were derived from four years (1987, 1988, 1990 and 1994). NDVI values of July images from those years not all were related with the climatic activities for the same calendar year. July of 1987 had the highest NDVI value (184.9) whereas the PDSI was 1.58. July of 1990 had the lowest NDVI values (154.1) whereas PDSI was 0.52. Both PDSI values were positive and above average. We found that NDVI values and PDSI index were inconsistent. In contrast, 1988 and 1994 had relatively high NDVI values (171.5 and 171.9) whereas PDSI values were negative (-2.06 and -0.89). As mentioned before, the PDSI index of -2.06 was the lowest value during thirty years, and 1988 was the recorded as the drought year. Because I had only four years of remotely-sensed data, this could not be analyzed the NDVI values statistically.

TABLE 9. *r*-value for correlation coefficient of climatic parameters vs. average ring width.

	TEMP	PPT.	PDSI	PHDI	ZNDX	PMDI
Mean Width	-0.19 ^{ns}	0.35*	0.57***	0.49**	0.49**	0.50**

ns = not significant; * = P<0.05; ** = P<0.01; *** = P<0.001

FIG. 9. Residual values as plotted against calendar years. Residual values were excluded age-related trend, which was corrected by simple linear regression. The graph shows the variation without age factor. Climatic response is more distinct in the residual values. Residual variation is shown in black line and the trend is shown in dotted line.

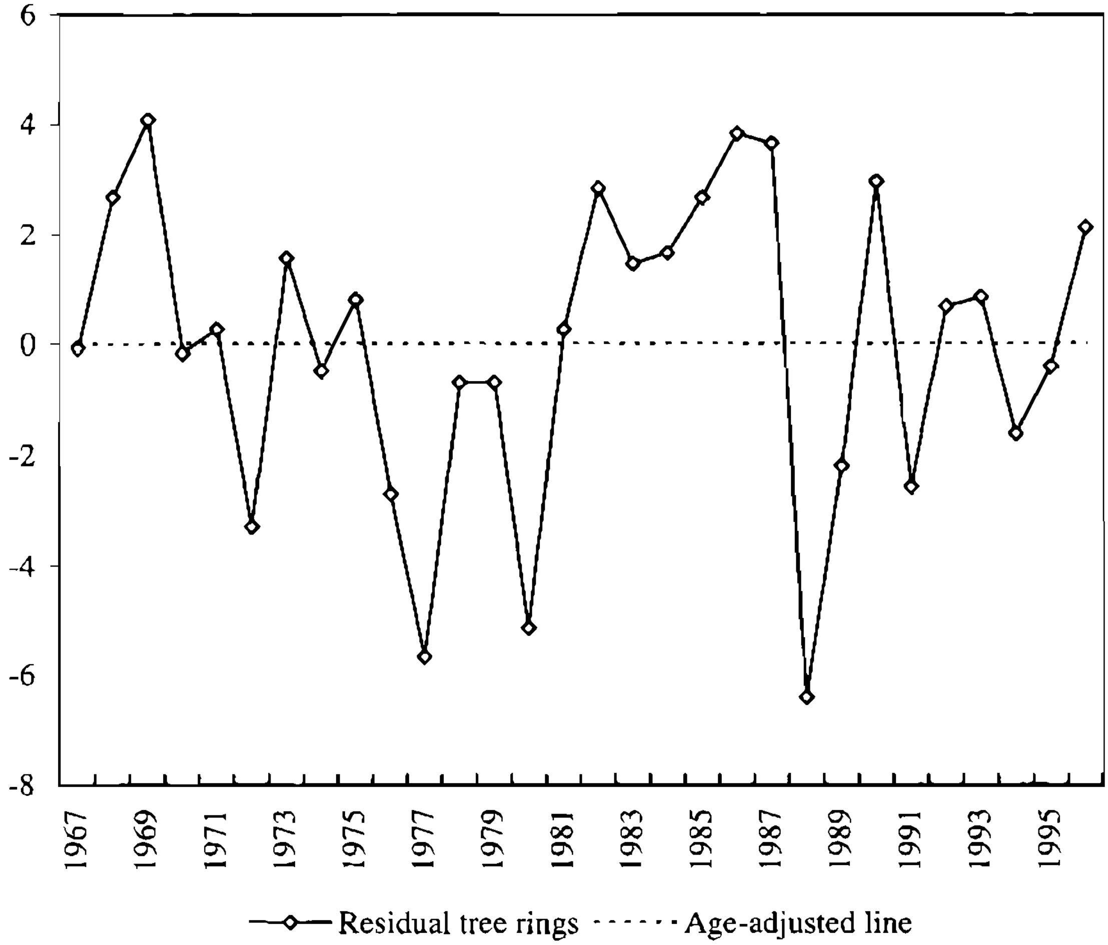
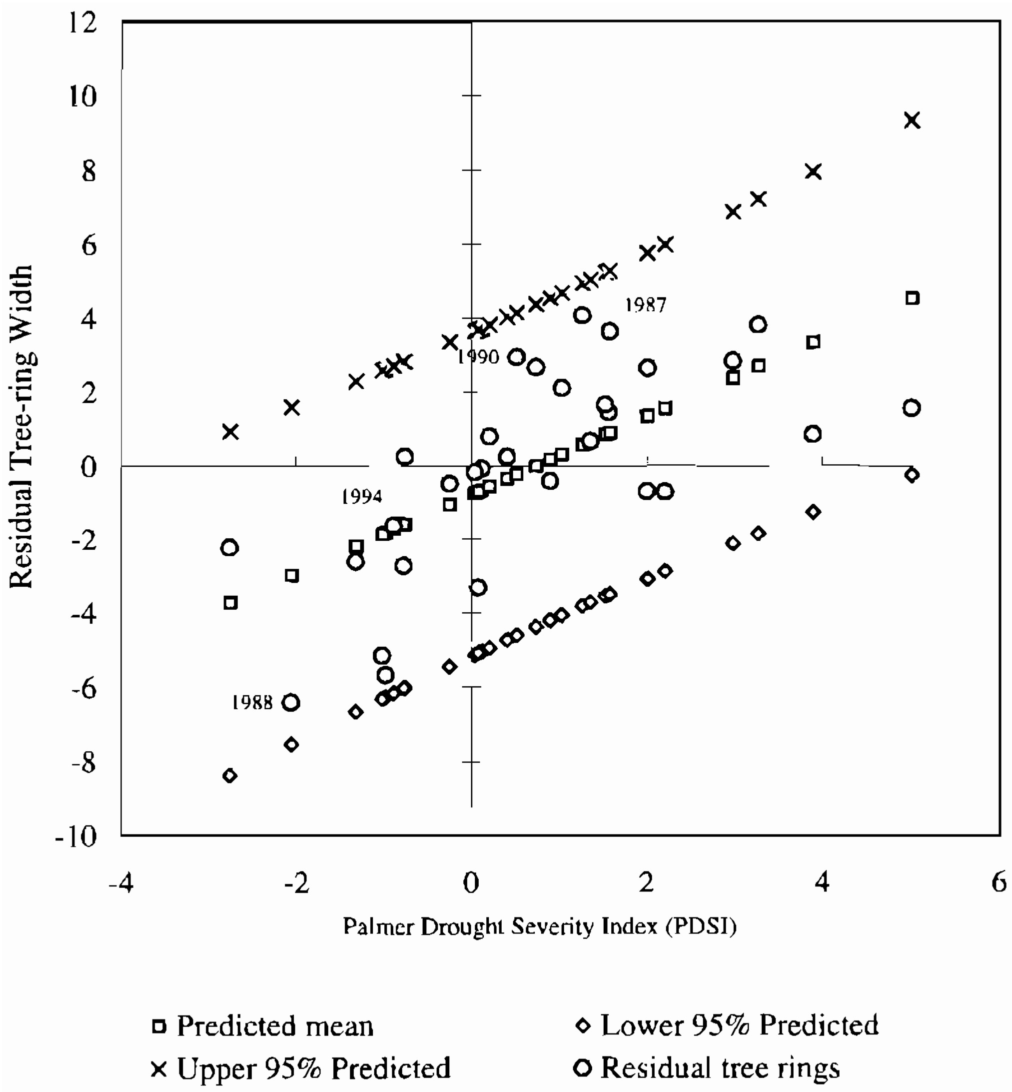

6
4
2
0
-2
-4
-6
-8
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
Residual tree rings
Age-adjusted line

FIG. 10. Residual, predicted values and 95% confident interval for tree-ring as plotted against PDSI. Tree growth was limited by PDSI. Predicted values were positively correlated with PDSI. As PDSI value decreased, predicted values for ring width decreased.



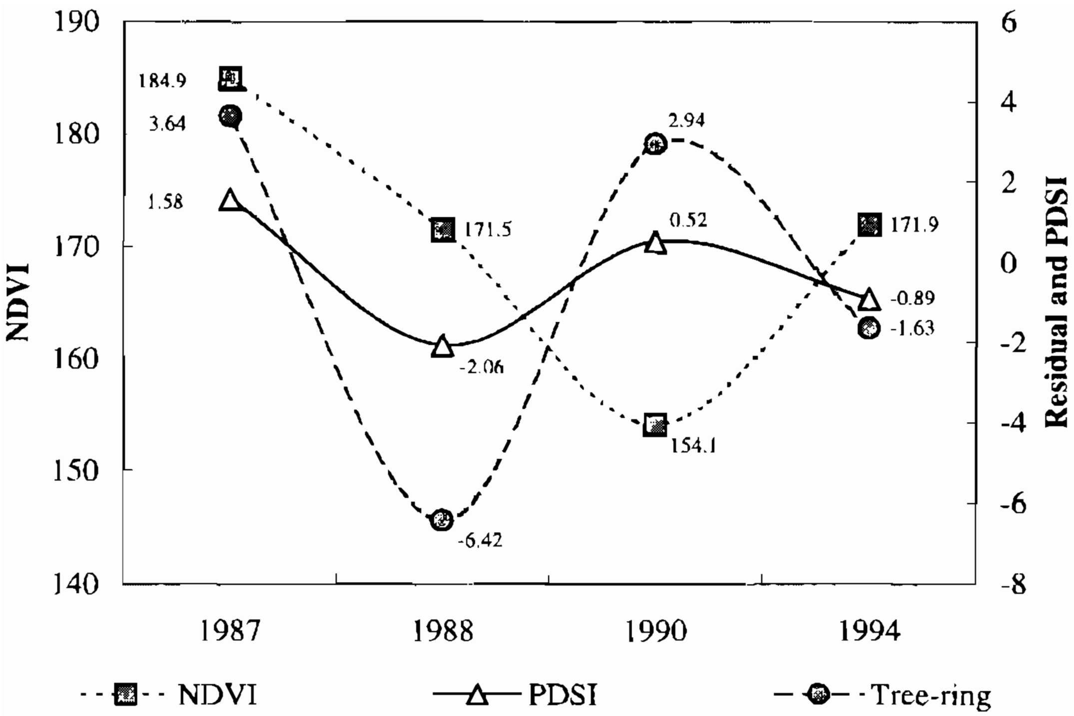
Residual Tree-ring Width
Palmer Drought Severity Index (PDSI)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-4
-2
0
2
4
6
1987
1990
1994
1988
Predicted mean
Lower 95% Predicted
Upper 95% Predicted
Residual tree rings

TABLE 10. *r*-value for Correlation Coefficient of Climatic Parameters vs. Residual Ring Width

	PPT.	PDSI	PHDI	ZNDX	PMDI
Residual Width	0.45*	0.67***	0.59**	0.59**	0.61**

* = P<0.01; ** = P<0.001; *** = P<0.0001

FIG. 11. PDSI affects on the residual ring width and NDVI were shown in the figure. Residual ring-width was strongly effected by PDSI. As PDSI decreased, residual ring-width decreased. Residual ring-width and PDSI values were the lowest in 1988. However NDVI were not effected by PDSI. Although PDSI was decreased in 1988, NDVI value did not decrease significantly. Likewise, PDSI was increased in 1990 while NDVI value decreased distinctly.



190
180
170
160
150
140
NDVI
6
4
2
0
-2
-4
-6
-8
Residual and PDSI
184.9
3.64
1.58
171.5
-2.06
-6.42
2.94
0.52
154.1
171.9
-0.89
-1.63
1987
1988
1990
1994
NDVI
PDSI
Tree-ring

DISCUSSION

Tree-ring records for oak species were significantly correlated with precipitation and drought indices, but not with temperature, suggesting that temperature was not a limiting factor for oak species in northeastern Kansas. These oaks withstood temperature changes from 7 °C to 20 °C that were well within the range of cold resistance for oak species (George and Burke 1976). Hardwood deciduous trees in a temperate region can survive temperatures as low as –40 °C (Burke et al. 1976), which did not occur during the study period. Extremely cold temperature inhibits tree-ring growth of woody plants at timberlines (Fritts 1976, Kramer and Kozlowski 1979). Boreal tree-ring records from high altitude can reconstruct annual temperatures in the Arctic (D'arrigo and Jacoby 1993). Abrupt temperature changes can injure some temperate trees (Salisbury and Ross 1992), however, no abrupt temperature changes occurred during the study period. Therefore, temperature variations apparently did not influence ring growth for the oak species in northeastern Kansas.

Tree-ring width was correlated with precipitation and drought indices. All of these indices were more strongly correlated with ring width than was precipitation alone. Precipitation data have been used to construct and analyze rainfall patterns relative to tree-ring growth (Stahle and Cleaveland 1992); however, it is not as sensitive a measure as PDSI. PDSI is a drought index, but it is also a measure of both soil moisture surplus and deficit and has been used to reconstruct climatic events from tree-ring chronologies (Cook 1979). The immediate effects of tree-ring growth responded closely to climatic change within a calendar year, although the climate of the previous year might also have affected woody growth (Fritts 1976).

In my study, the variations of ring width were synchronized with the climatic patterns. Widths of rings decreased in the drought years 1977, 1980, and 1988. In those years, conditions were not favorable for ring growth as shown by negative residual widths. Because of the correlation between the PDSI and tree-ring width drought is probably the limiting factor for the oak species in the Leavenworth study area. Growth of ring widths declined in years with negative PDSI values. In a dendroclimatology study in the southeastern United States, Stahle and Cleaveland (1992) found that rainfall was a stronger climatic variable on bald cypress (*Taxodium distichum*); however, drought was not a factor in their study. Aber et al. (1981) found that annual tree-ring growth in Ponderosa Pine (*Pinus ponderosa*) in northeastern Nebraska was influenced by the amount of snowfall during the preceding winter.

Precipitation was high in 1977, however ring-growth did not increase because the PDSI value was negative. Years of strong woody growth were 1969, 1973, the mid-1980s, and 1990. In those years, PDSI values were positive. Sustained growth occurred with the combination of warmer temperature and high moisture content, which is favorable for high productivity (Salisbury and Ross 1992). The PDSI was the variable that influenced tree growth most strongly. Tree growth, as evidenced by ring width, responded immediately to climatic variation within the same calendar years.

NDVI values were not correlated with PDSI, and a lag effect of one to two years after a drought season was observed. Tree-ring growth was strongly correlated to PDSI, and showed immediate response to the climatic events. However, NDVI values, which depict the vegetation biomass, i.e., tree leaves, were not synchronized with the annual climate. The 1987 NDVI value was the highest among the study years. Oak trees showed good ring growth in this particular year. The year 1987 had favorable climatic conditions with positive PDSI. The high NDVI value for 1987 might be the result of previous vigorous growth during the 1980s when ring growth was influence by good climatic conditions. NDVI in 1988 was relatively high, even though 1988 was a drought year, when ring-growth decreased significantly.

Vegetative growth, as reflected in the density of leaves in the forest canopy, was high in leaf elongation in pines and leaf expansion, because of previous favorable conditions (Garrett and Zahner 1971). Ring growth was immediately effected by the drought conditions in 1988, but vegetation growth was not effected that year. Climatic conditions of 1980s were favorable, and ring growths were well above average. Vegetation growth did not show the current climate effect but appeared to be effected one or two years later. NDVI values were influenced by the time that an image was taken. Late spring images had the highest, and autumn images had the lowest NDVI.

Spring was the time for new growth, initiated from leaf primodia of the previous year. Thus, vegetation growth in spring was not influenced by current weather conditions. As vegetation growth increased, cambial growth increased because the amount of leaf surface area and metabolic activities of leaves affect cambial growth. Kozlowski (1971) found a high correlation between the cambial growth of trees and a seasonal increase in leaf product that produced vigorous growth early in the growing season. However, when leaves are exposed to unfavorable conditions, i.e., drought, they reduce their leaf surface area by defoliation and by changing their arrangement of exposure to the sunlight (Salisbury and Ross 1992). As leaf activity decreased, cambial growth also decreases because defoliation inhibits the xylem production (Kozlowski

1971). Xylem production is reduced proportionally when defoliation is incomplete, and ceases entirely when the leaves fall. Therefore, latewood formation depends on the timing of defoliation.

In this study, NDVI values were highest in late spring, and the lowest in autumn. Because water content in the leaf affects the reflectance of wavelength (Larsson 1993), water content in the leaf can be detected for the season. NDVI values for late growing seasons might have some correlation with cambial growth of the next season. However, only two autumn's images, October 1988 and September 1994, were available, and I was unable to analyze the data for late growing seasons.

CONCLUSIONS

Removing age factors improved the analysis correlating ring-width growth and climatic variations. Growth of tree rings responded immediately to the climatic variation of the same year. Tree growth was significantly influenced by PDSI but not by temperature, and precipitation was not as strong a factor as PDSI for tree growth. Woody growth and leaf growth responded to climate differently. Leaf growth, as measured by NDVI, showed the effects of previous year is climatic conditions. NDVI values did not correspond with PDSI values, indicating that leaf growth was not influenced by current year climatic events. Response of leaf growth lagged one or two years behind a severe climatic event.

Ground observation, i.e., dendroclimatology, showed that NDVI values were out of phase with the climatic pattern. Thus, growth of the tree canopy is not immediately effected by the current climate. NDVI value therefore should be used with caution in interpreting climatic effects on forest growth. A continuous series of remote sensing datasets are required to fully interpret the lag effect and the full spectrum of forest response to climate. Seasonal changes of spectral signature can be used to correlate NDVI and the growth of tree-ring.

Although my study was limited to only one forest site, and I would suggest that whereas tree-ring growth responded closely to climatic events of the same year, forest canopy growth might reflect the conditions of previous years. This lag phase in forest growth response could be important for recovery from severe climatic stresses.

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Appendices

APPENDIX A. Average Ring-widths and their calendar years

Year	Average	Residual Values
1967	25.44	-0.07
1968	28.00	2.67
1969	29.22	4.07
1970	24.80	-0.17
1971	25.04	0.25
1972	21.30	-3.30
1973	25.98	1.56
1974	23.76	-0.48
1975	24.86	0.80
1976	21.16	-2.72
1977	18.02	-5.68
1978	22.82	-0.69
1979	22.64	-0.69
1980	18.00	-5.15
1981	23.22	0.25
1982	25.62	2.83
1983	24.06	1.45
1984	24.08	1.65
1985	24.90	2.66
1986	25.88	3.82

APPENDIX A. Average Ring-widths and their calendar years (Cont.)

Year	Average	Residual Values
1987	25.52	3.64
1988	15.28	-6.42
1989	19.30	-2.22
1990	24.28	2.94
1991	18.56	-2.59
1992	21.64	0.67
1993	21.64	0.85
1994	18.98	-1.63
1995	20.02	-0.41
1996	22.36	2.11

APPENDIX B. Average Climatic Data – Kansas Division 3

Year	TEMP	PPT.	PDSI	PHDI	ZNDX	PMDI
1967	52.45	39.70	0.12	-1.28	0.37	-0.55
1968	52.48	36.15	0.74	1.04	0.53	1.00
1969	51.75	34.08	1.27	2.15	0.27	1.71
1970	53.00	34.19	0.04	-0.08	0.02	-0.07
1971	52.79	28.66	-0.76	-0.65	-0.40	-0.42
1972	51.86	35.79	0.08	-0.19	0.49	0.27
1973	53.42	55.35	5.01	5.01	2.37	4.92
1974	53.50	28.15	-0.25	2.65	-0.49	1.66
1975	52.91	33.50	0.21	0.56	0.16	0.01
1976	53.01	23.79	-0.77	-0.69	-0.89	-0.83
1977	53.81	46.50	-0.98	-1.26	0.31	-1.12
1978	51.04	34.64	2.21	2.21	0.31	1.94
1979	50.47	35.67	2.00	2.00	0.63	1.66
1980	53.78	29.99	-1.02	-0.64	-0.46	-0.69
1981	54.19	38.25	0.41	0.02	0.43	0.28
1982	51.52	41.26	2.98	2.98	1.17	2.86
1983	52.41	34.56	1.57	1.60	0.22	1.58
1984	53.06	38.21	1.53	1.25	0.48	0.63
1985	51.00	44.29	2.01	2.01	1.20	1.48
1986	55.70	46.37	3.27	3.27	1.14	3.12

Appendix B. Average Climatic Data - Kansas Division 3 (Cont.)

Year	TEMP	PPT.	PDSI	PHDI	ZNDX	PMDI
1987	55.50	37.20	1.58	2.86	0.36	2.49
1988	54.26	19.22	-2.06	-1.61	-1.59	-1.89
1989	52.34	30.56	-2.76	-4.55	-1.15	-4.11
1990	55.08	35.67	0.52	-0.39	0.31	0.21
1991	55.13	28.48	-1.32	-1.75	-0.73	-1.46
1992	53.57	41.86	1.36	1.02	1.09	1.17
1993	51.69	53.97	3.89	5.36	2.11	5.32
1994	53.72	26.67	-0.89	1.42	-0.58	0.82
1995	52.85	39.59	0.90	1.27	0.69	1.13
1996	51.72	39.03	1.03	1.18	0.76	1.03

Climate Division Drought Data - Graphing Options,

http://www.ncdc.noaa.gov/ol/climate/climatedata.html

http://www.ncdc.noaa.gov/onlineprod/drought/main.html

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