SPATIAL CLUSTERING OF FALSE RING ANOMALIES IN *JUNIPERUS VIRGINIANA* OF THE OKLAHOMA CROSS TIMBERS

By

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IN *JUNIPERUS VIRGINIANA*

OF THE OKLAHOMA CROSS TIMBERS

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Abstract: This study counted false rings in eastern redcedar samples to track growing conditions in the Cross Timbers of Oklahoma. Using ArcGIS, this study expands on previous research that used comparison between two sites and examines trends across the Cross Timbers region of central Oklahoma. Kriging analysis was used to compare atmospheric data from the Oklahoma Mesonet to tree core data. False rings are a type of growth anomaly that occurs in certain species of trees, particularly evergreens. These anomalies result from periods of water stress that cause the tree to begin forming late wood, followed by late season precipitation that causes the tree to revert to its normal growth pattern. False rings can indicate areas prone to a high degree of climatic variation. The highest occurrence of false rings was found on the boundary between the driest and wettest regions. These areas were not subjected to prolonged periods of drought, but did experience some degree of water stress. This may be useful in identifying areas prone to sudden shifts in growing conditions and providing greater seasonal resolution of dendroclimatic models. This trend was the strongest with vapor deficit, where the highest and lowest levels produced almost no false rings, but the mid-range levels produced large quantities of false rings. False ring probabilities were tracked using 553 samples from eastern redcedars growing in eleven sites throughout central Oklahoma. The false ring records counted in these cores were compared to weather records collected through the Oklahoma Mesonet. Maps of weather averages were constructed using Kriging analysis on records from 1994 to 2008.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The objective of this study is to identify patterns in the occurrence of ‘false ring’ growth anomalies in eastern redcedar (*Juniperus virginiana*) in the Oklahoma Cross Timbers region [Fig 1]. The study presented here builds on false ring research conducted by Edmondson (2010) on eastern redcedar (ERC) at Keystone Ancient Forest Preserve in northeastern Oklahoma and Cedar Bluff Reservoir in central Kansas. Although other studies (Copenheaver et al. 2010; Edmondson 2010) have investigated false rings using binary comparisons of sites in two discrete regions, there remains a lack of research investigating distribution of false rings across a contiguous region. This study seeks to fill that gap by comparing false ring distributions across the Cross Timbers forests to equivalent atmospheric data using archived samples collected for a previous study (DeSantis and Hallgren 2010).

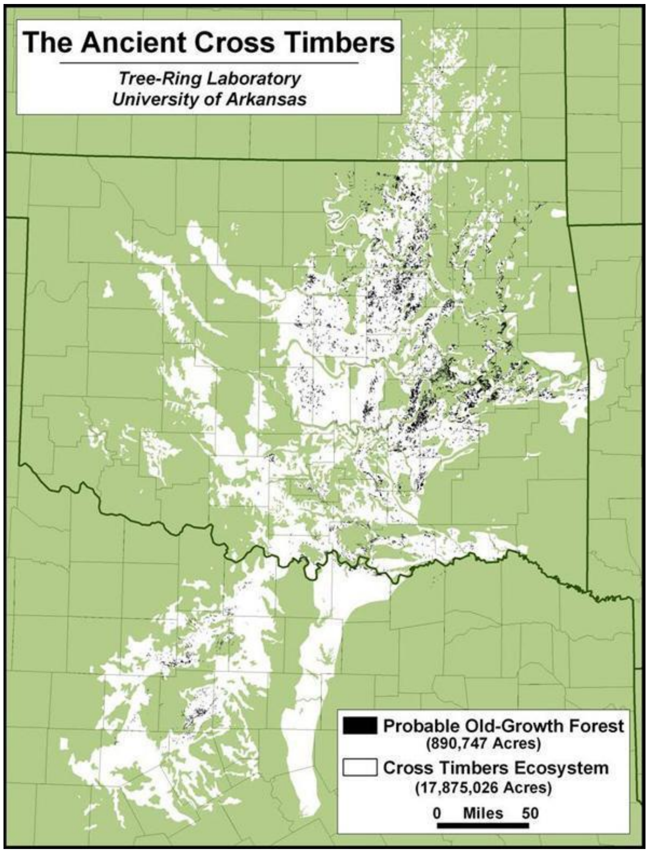

Figure 1: Map of Cross Timbers region. University of Arkansas Tree-Ring Laboratory. http://www.uark.edu/misc/xtimber/map/

False rings

False rings are anomalies in a tree's growth patterns, produced by stress on the tree. Copenheaver et al. (2006) describe false ring morphology as follows:

In conifers, false rings appear as a narrow band of thick-walled tracheids (latewood) surrounded on both sides by thin-walled, large diameter tracheids (earlywood). The boundary between the earlywood cells that follow the false ring exhibits a more gradual increase in cell diameter and decrease in cell wall thickness than the abrupt change in cell diameter associated with a true ring boundary.

Tree rings are the result of variations in the growth of the cells in the cambium of a tree. During the highly productive periods of the growing season, the tree produces large cells with relatively thin walls. At the end of the growing season temperature and precipitation drop, in response the cells produced by the tree become smaller with thicker walls [Fig 2]. Water stress earlier in the growing season can produce similar growth responses, if the stressful conditions cease then the tree will resume its normal growth pattern leaving behind a false ring (Edmondson 2010;). Other anomalies such as frost damage and fire can be recorded in the rings of the tree. Damage from herbivorous insects has been shown to contribute to false rings in some species of conifer (Gonda-King, Radville, and Priesser 2012). The anatomical structures of the climate induced false rings are easily distinguished from frost and fire damage, while rings from insect damage can be ruled out through crossdating against other trees in the stand.

Figure 2: Image of annual ring (left) and false ring (right)

Eastern Redcedar

A member of the Cupressaceae family, ERC is the most common evergreen east of the Rocky Mountains (Lawson 2004). The tree has a range that extends from the Atlantic Ocean to the Cross Timbers in Oklahoma and Texas. Along the Atlantic, the trees can be found from the Carolinas to Nova Scotia and west into the Great Plains [Fig 3].

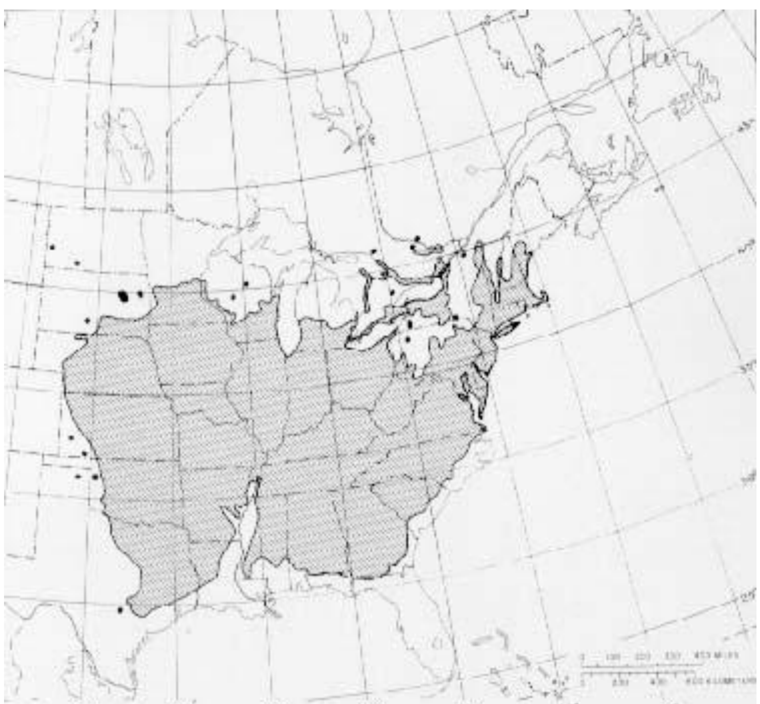

Figure 3: Distribution of ERC from Forest Service silvics manual

The ERC has become notorious in the rangelands for its aggressive growth, encroachment into grassland, and rapid colonization. ERC trees were once kept in check by fires, but human fire prevention methods have created an opportunity for ERC to become invasive in grasslands and oak forests (DeSantis et al. 2011).

ERC is used in this study because it is the only abundant tree in the Cross Timbers that produces false rings (DeSantis et al. 2010). Post oak (*Quercus stellata*) and blackjack oak (*Quercus marilandica*) are common in the Cross Timbers, but they do not produce easily identifiable false rings, making them less useful for tracking water stress. Some conifers such as loblolly pine (*Pinus taeda*) are native to the Cross Timbers, but do not appear frequently enough to provide useable data.

Cross Timbers

The Cross Timbers ecosystem is a patchy mix of forests and grasslands that occur between the high plains and the Ozark forests. The Cross Timbers mostly occur in Oklahoma and extend into Kansas, Arkansas, and Texas [Fig 1]. ERC has become increasingly common in the xeric forests of the Cross Timbers as fire culling has become less prevalent. This reduction of fire has shifted the proportion of *Juniperus* compared to the previously dominant *Quercus* species in the Cross timbers (DeSantis, Hallgren, and Stahle 2011).

Objectives

Given the usefulness of false tree rings in *Juniperus* for recording droughts during the mid-growing season (Edmondson 2010), this study encompassed the following objectives:

- Analyze *Juniperus virginiana* cores from the Oklahoma Cross Timbers, focusing on false-ring events from 1998 to 2008 and comparing them to temperature, rainfall, and vapor deficit
- Identify any regionality present in recorded false-ring events (esp. east-west variation)
- Identify significant correlations with atmospheric measurements recorded by the Oklahoma Mesonet

Mesonet

Activated in 1994, Oklahoma's Mesonet system provides detailed records of weather events for the time that it has been operational. The Mesonet includes at least one monitoring station for each county in Oklahoma. The stations are able to monitor weather data including temperature, precipitation, and pressure. Elevation

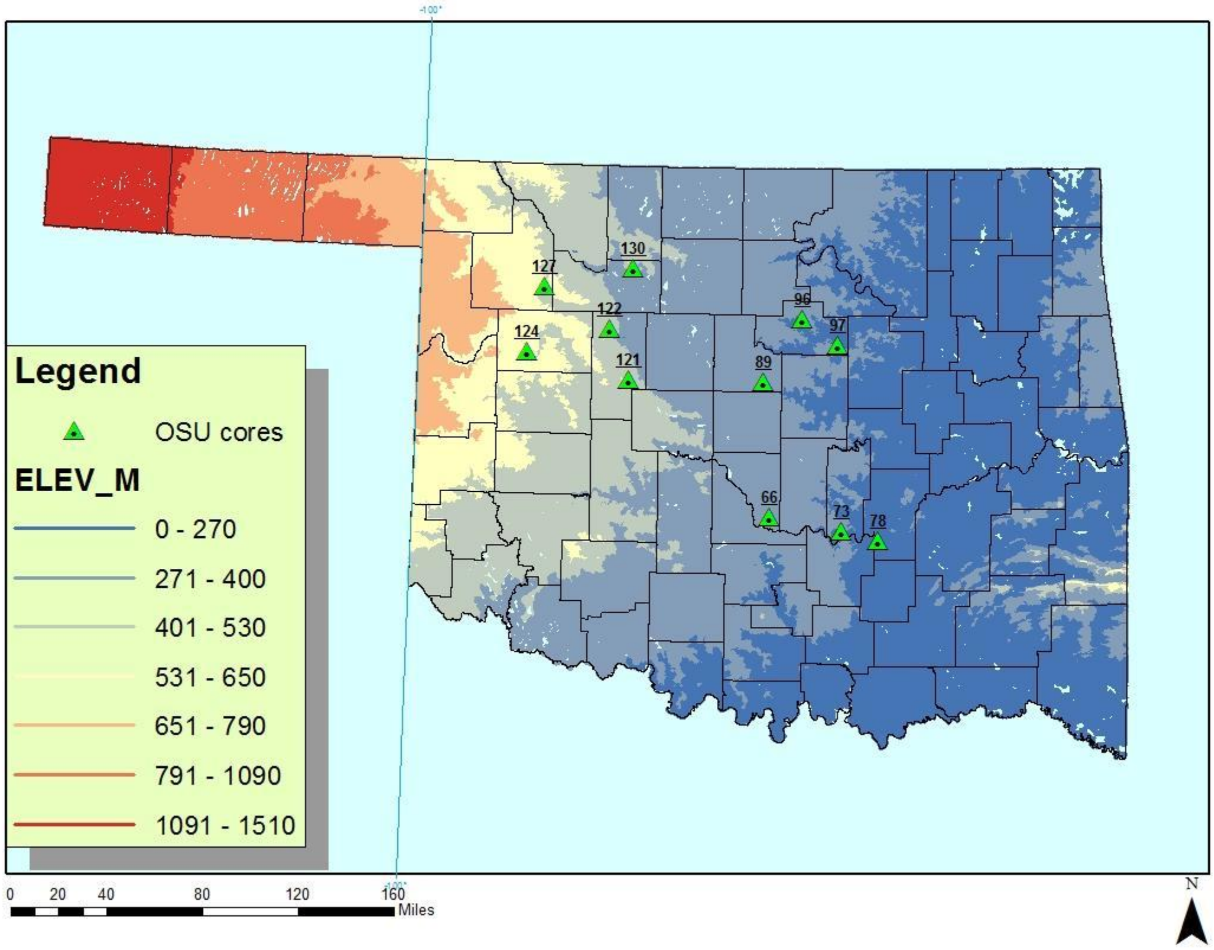

Figure 4: Elevation map of Oklahoma (meters)

Oklahoma's elevation trends upward to the west. The highest point is located at Black Mesa in Cimarron County, in the extreme west of the panhandle. The lowest point is located just south of the Ouachita Mountains in the southeast corner of the state [Fig. 4]. The sample sites follow this east-west trend, with the western sample sites at noticeably higher elevations than the other sites (Appendix I).

CHAPTER II

LITERATURE REVIEW

Previous studies of the Cross Timbers have focused on ring samples from post oak (*Quercus stellata*) and blackjack oak (*Quercus marilandica)* (Clark and Hallgren 2004). However, only ERC (*Juniperus virginiana*) provides clear false ring patterns. Loblolly pines (*Pinus taeda*) and shortleaf Pine (*Pinus echinata*) are found in the southeastern corner of Oklahoma, but are not prevalent in the Cross Timbers. Because of this limited variety, ERC is the only species useful for this study.

Cross Timbers geography and ecology

The Cross Timbers region is a patchwork of grass and xeric forests, primarily located in Oklahoma and Texas, and extending to Kansas and Arkansas [Fig. 1]. Historically the region was largely occupied by oak forest primarily comprised of post oak (*Quercus stellata*) and blackjack oak (*Quercus marilandica*). In recent years, the composition of the Cross Timbers has shifted towards greater diversity, with post and blackjack oak becoming less prominent compared to species like ERC (DeSantis et al. 2010, DeSantis, Hallgren, and Stahle 2011).

Climate

If you don't like the weather in Oklahoma, wait a minute and it'll change.

-Will Rogers

Oklahoma is known for unpredictable weather. This is particularly true of the Cross Timbers region (Francaviglia 2000). Peak rainfall occurs in late April and May, while highest temperatures occur in late July and August. The highest temperatures in the study area occurred in 2006. 2006 and 2001 had notably low rainfall with 2006 being the slightly drier year.

The climate that a tree is exposed to during the growing season is a major contributor to growth anomalies such as false or missing rings (Bogino and Bravo 2009). Extreme temperatures, drought, or flooding can lead to such anomalies. Cold temperatures can produce frost rings and sun scald. Sun scald is a splitting of the bark on a young tree that is exposed to cold nighttime temperatures; when exposed to sunlight, the illuminated side of the tree warms and expands faster causing stress that splits the bark of the tree (Harvey 1923). High temperatures and lack of rainfall contribute to false rings and fire damage. Flooding can cause physical damage, encourage fungus, and interfere with gas exchange in root systems. Microclimate plays a significant role in tree growth. Copenheaver et al. (2005) found significant differences in the growth of ERC in the interior and on the edge of a stand.

Bogino and Bravo (2009) found that January to November precipitation had a significant influence on the occurrence of growth anomalies in *Pinus pinaster.* Edmondson (2010) found that, "significant false ring events . . . occurred when there was an intense heat wave and drought during the mid-growing season, followed by an unseasonable cool-wet spell when daily maximum temperatures fell as much as 16˚C (29°F) and heavy rainfall often occurred”(Edmondson 2010: 31).

Soils and geology

ERC is very well adapted to the prevalent conditions of the Cross Timbers region. DeSantis, Hallgren, and Stahle (2011: 1834) report the Cross Timbers region as, "[f]ine-grained clay soils with limestone and shale parent material generally support grasslands and coarse-grained sandy soils with sandstone parent material generally support forests." However, Dirr (1998) reports that ERC also performs very well in limestone based soils. In essence, while the two most important woody species of the Cross Timbers, blackjack oak and post oak prefer sandy soils, ERC can grow in most soil types. This adaptability is part of why ERC has been so successful in colonizing new areas and encroaching on existing xeric forest. Most of the sites in the study are located on fluvial aquifers of the Canadian, North Canadian, and Cimarron rivers. Three sites are located on the Garber-Wellington and Vamoosa-Ada aquifers [Fig 5]. These aquifers are principally comprised of Permian and Pennsylvanian sandstone, respectively (D'Lugosz and McClaflin, 1986; Mashburn et al. 2013)

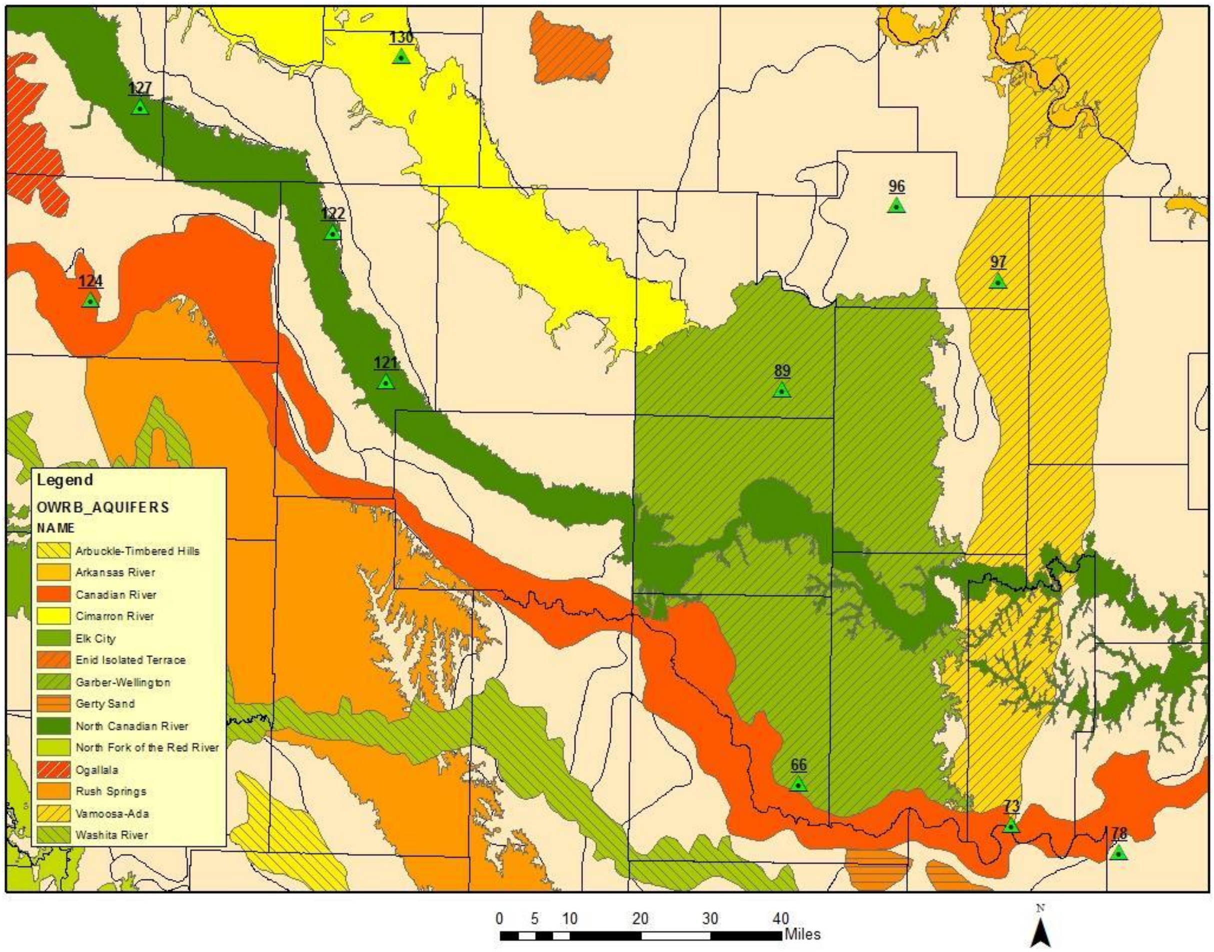

Figure 5: Map of aquifers in the study area

ERC dispersal

ERC (*Juniperus virginiana*) is the most common conifer in North America. It is considered a nuisance species in many grassland environments due to its tendencies towards aggressive colonization and providing a host for cedar-apple rust, a detrimental fungus for apple orchards.

The largest specimen in the United States is located at the Lone Hill United Methodist Church in Georgia, with a circumference of 234”, a height of 57’, and a crown diameter of 75’ (Georgia Forestry Commission, 2007). The species is able to tolerate low water and high levels of $CaCO_3$. ERC has been shown to effectively colonize stone cracks and other sheltered areas (Livingston 1972). The species manifests male and female specimens, differentiated by blue berry-like cones on the females and small brown pollen sacs on the males (Dirr 1998).

The Cross Timbers ecosystem is a mix of grassland and forest. The previously oak dominated forests of the Cross Timbers have shown an increase in woody plant diversity over the last 100 years, largely due to fire suppression (Engle, Bidwell, and Moseley 1996; DeSantis et al. 2010; DeSantis, Hallgren, and Stahle 2011). Over 65% of ERC seed crops are dispersed away from the tree by songbirds (Chambers, Vander Wall, and Schupp 1999); cedar waxwings (*Bombycilla cedrorum*), robins (*Turdus migratorius*), and mockingbirds (*Mimus polyglottus*) are the primary dispersal agents (Phillips 1910; Horncastle et al. 2004). These birds are one reason ERC are often clustered along fence lines, the birds perch on the fence and deposit the seeds. These fence lines also provide some cover for saplings, by discouraging large grazing animals from trampling the saplings (Chambers, Vander Wall, and Schupp 1999). ERC cones and seeds have also been recorded in the feces of raccoons (*Procyon lotor*), foxes (*Vulpes* spp.), bobcats (*Lynx rufus*), and various other small mammals (Phillips 1910).

Ring Anomalies

The structure of a tree's rings results from a mix of environmental and genetic factors. The response to environmental conditions will differ between species. Some species will produce unique patterns in response to outside influences. However, there are different types of anomalies depending on the external factor influencing wood ring growth. The most common anomalies and their distinctive characteristics are described below.

False Rings

False rings are often considered "noise" when performing dendrochronological analysis; studies have been conducted comparing false rings between two different sites (Copenheaver et al. 2010, Edmondson 2010). False rings are also referred to as 'double rings,' (Douglass 1928) 'multiple growth layers,' (Glock 1955) 'intra-annual growth bands,' (Fritts 1976) 'and intra-annual density fluctuations' (Campelo et al. 2006). Other studies have investigated causes of these rings. Gonda-King, Radville, and Preisser (2012) found that infestation by herbivorous insects, namely Hemlock woolly adelgid (*Adelges tsugae* Annand) and elongate hemlock scale (*Fiorinia externa* Ferris) may cause an increased incidence of false rings in American Hemlock (*Tsuga Canadensis* (L.) Carrière*)*. False ring studies have been performed on trees in the genus *Pinus* (Campelo et al. 2006; Oberhuber and Gruber 2010, Marchand and Fillion 2012). Wimmer, Strumia, and Howlawe (2002) found that false rings in Austrian pines (*Pinus nigra*) relate to low precipitation in May, particularly when high rainfall occurred in April and June. Copenheaver et al. (2006) found no significant climatic influence in the formation of false rings in *Pinus* *banksiana*, but deemed the anomalies useful for reconstructing factors such as stand density and canopy formation.

Frost Rings

Frost rings were observed in a small number of samples from this study. These are layers of ruptured cells, similar to desiccation rings that are produced when late frosts occur in the early growing season after the tree has come out of its dormant state causing the water in the xylem to freeze and ruptures the cells (Stahle 1990). Since these event occur early in the growing season, they appear near the latewood of the previous year's growth.

CHAPTER III

METHODOLOGY

In order to demonstrate a trend in growth anomalies relative to temperature, precipitation, and vapor deficit, it is necessary to compare the pattern of false rings to trends in meteorological records. A control site is unfeasible, so it is necessary to compare sites around the state that have been subjected to different conditions to identify trends and patterns. Vapor deficit is the strongest representative for drought stress, but it is worth investigating precipitation and temperature patterns. By examining the timing and distribution of these conditions, we may establish a correlation between false ring occurrence and specific climatic patterns during the growing season.

Data Sources

This study used archival atmospheric data and tree core samples collected for another study. The climate data is taken from the Oklahoma Mesonet. The mesonet was selected due for its statewide coverage and high resolution. The tree core samples stored in the Forest Ecology lab at Oklahoma State University were originally collected by Dr. Ryan DeSantis for his PhD research (DeSantis et al. 2010; DeSantis, Hallgren, and Stahle 2011) , and reanalyzed for this study with permission.

This study focuses on climatic influences during the growing season, so atmospheric values for the sample sites use the Mesonet records from March 1 to September 30 values from 1994 to 2008. The stations in Vanoss and Tulsa were omitted due to lack of data for the study period.

The stations in the Oklahoma panhandle (Slapout, Beaver, Hooker, Goodwell, Boise City, and Kenton) were too remote to significantly affect the calculations for the study area, but would result in distorted maps with a misleading degree of homogeneity in North Texas [Fig 6].

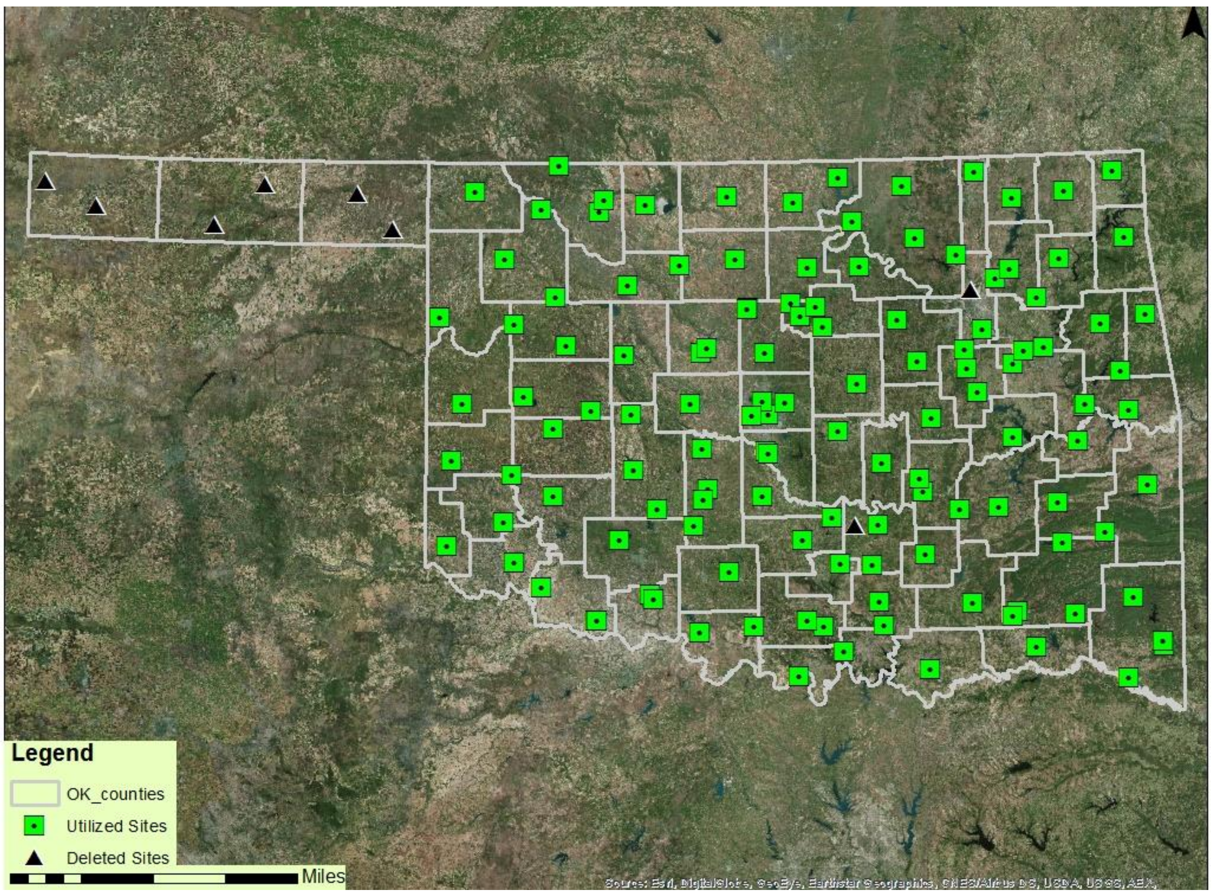

Figure 6: Map of Mesonet stations used in and omitted from atmospheric calculation

Samples

The samples collected by DeSantis include post oak, blackjack oak, black walnut, birch, and ERC. These samples are from 11 sites around the Cross Timbers [Fig 7]. The juniper samples include

334 cores and 219 disks. The locations used in this study were originally studied by Rice and Penfound (1955, 1959) and revisited in 2008 and 2009 (DeSantis et al. 2010; DeSantis, Hallgren, and Stahle 2011).

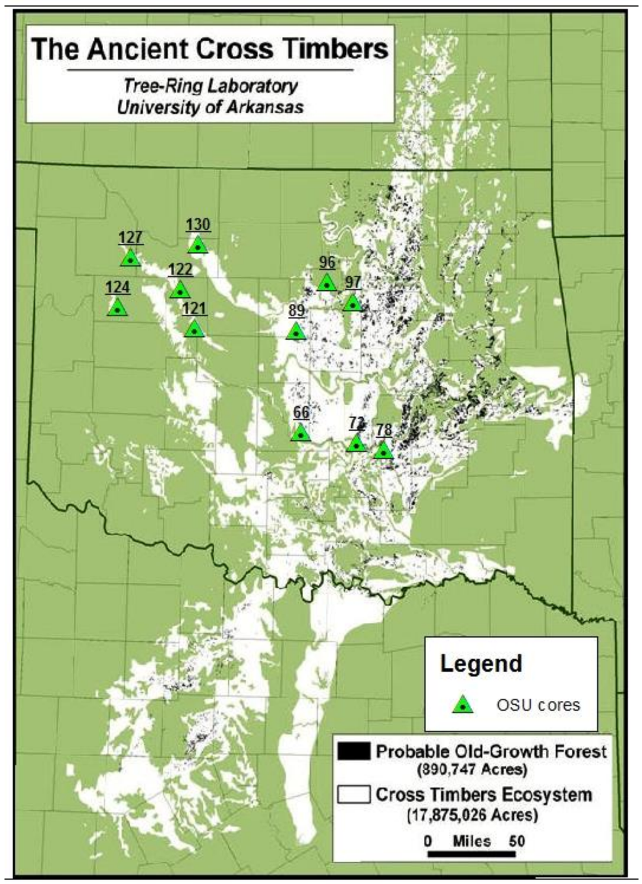

Figure 7: Location of study sites.

Sample processing/Data Collection

The core samples were mounted and sanded with progressively finer abrasive paper, until the cell structure was visible through magnification. This processing was done for the original studies by DeSantis, however this project required higher magnification in order to confidently identify xylem morphology so additional sanding was necessary. Improperly mounted samples were removed from the data set.

The false rings in each sample were counted and logged in an Excel spreadsheet. Only anomalies showing a progressive increase and decrease in cell density were counted as false rings. Frost rings, fire damage, and light rings were ignored. The number of false rings in each year was counted, and then the probability of any false rings in a particular year was calculated [Table 2].

Table 1: Ratio of false ring samples to total samples by year and site

Site	2008	2007	2006	2005	2004	2003	2002	2001	2000	1999	1998
66	42/56	21/56	33/56	21/56	23/56	36/56	49/56	40/56	36/56	38/56	32/56
73	09/50	22/50	13/50	18/50	28/50	17/50	34/50	35/50	19/50	26/50	15/50
78	13/52	17/52	11/52	09/52	13/52	17/52	12/52	19/52	12/52	13/52	10/52
89	23/53	25/53	68/53	37/53	13/53	27/53	28/53	23/53	21/53	23/53	41/53
96	08/49	15/49	14/49	16/49	05/49	07/49	13/49	11/49	11/49	08/49	11/49
97	20/49	19/49	20/49	26/49	19/49	25/49	21/49	23/49	20/49	22/49	31/49
121	23/73	26/73	23/73	21/73	11/73	28/73	33/73	23/73	20/72	14/71	19/71
122	20/58	35/58	15/58	22/58	09/58	11/58	20/58	06/58	10/58	20/58	30/58
124	06/23	22/23	10/23	04/23	03/23	02/23	02/23	04/23	01/23	13/23	14/23
127	37/65	24/65	55/65	32/65	15/65	11/65	02/65	09/65	07/65	18/65	26/65
130	40/64	46/64	37/64	40/64	31/64	27/64	39/64	38/64	52/64	40/64	36/63

Analysis

False ring data from each site was calculated by year and compared to false ring values from other sites by year. A Pearson's *r* value was calculated for each pair of sites. Correlations to weather records at nearby Mesonet stations were also calculated for each site by year. These correlations were entered into ArcMap to check for spatial clustering using visual analysis.

Calculations

In order to account for different sample sizes across differing years and sites, the percentage of false rings was calculated using the number of samples with false rings for a given year at a particular site divided by the total available samples for the given year at that site [Table 2]. Tree-ring data similarities between sites was tested using the Pearson correlation and chi-square tests. SPSS 19 was used to sort and conduct first and second order analyses on the Mesonet and false ring data. Maps were constructed in ArcMap 10 using the Kriging tool.

Interpolation

Temperature, precipitation, and vapor deficit maps for the study area were constructed using Mesonet data. Maps were constructed using kriging analysis in ArcMap. These maps were used to demonstrate spatial distribution of climatic trends, not for statistical tests which instead used an unweighted average from mesonet sites within 30 miles of each sample site.

Correlation/ Limitations

While the study includes over 500 individual samples, there are only 11 core sites, limiting the options for statistical analysis such as p-test and limiting the options for multivariate analysis such as Nearest Neighbor Analysis. Pearson correlations were used to test for spatial clustering in the occurrence of false rings and for correlation to Mesonet records.

CHAPTER IV

RESULTS

There is a spatial trend in the similarity and occurrence of false rings in the ERC of the Oklahoma cross timbers. Two patterns appear when the data is mapped. The similarity between the samples seems to correlate with latitude. A Pearson correlation showed two distinct groupings in the northern and southern sites of the study area [Fig 8].

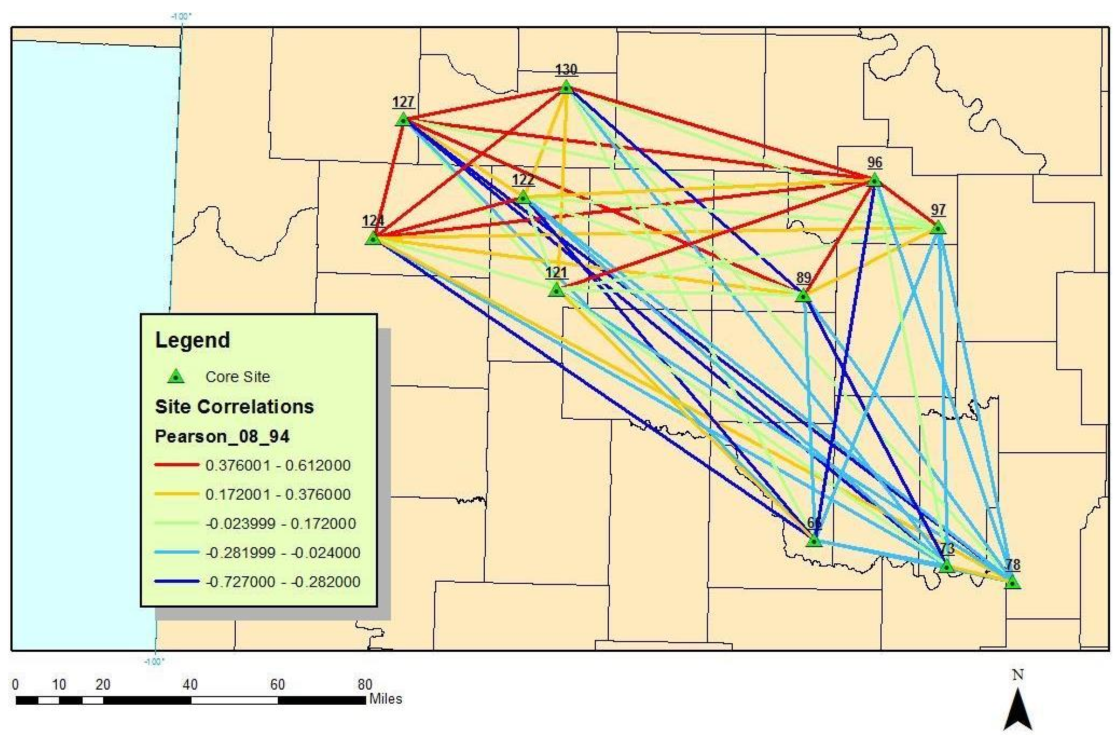

Figure 8: Pearson correlation between sample sites

The raw false ring count is noticeably lower in the western sites. There does not appear to be a strict correlation with longitude as site 130 has a relatively high percentage of false rings and the sites in the east are fairly varied [Fig 9].

Statistical test

The distribution of false rings was tested using chi-square (χ^2), pearson correlation, and binary regression tests to determine the value. A binary regression analysis comparing false ring totals to averages of vapor deficit from the Mesonet sites within 30 miles of the sample site produced no significant results. The χ^2 tests presented here demonstrate that although the samples used for this study are not truly random, they are diverse enough to mitigate concerns about selection bias in the sample set.

χ^2 test

χ^2 tests were performed on the age of the samples and the frequency of false rings in order to confirm that the sample sets were heterogeneous [Table 3]. The number of years displaying false rings was counted and second order values calculated. The mean for samples across all sites from 2008 to 1903 was 6.24 with a standard deviation of 4.48. Samples were divided into four categories (A, B, C, D) based on the number of false rings present, using the mean and the positive/negative value of one standard deviation as break points. The results of this test indicate the probability of a Type 1 error at < 0.001, rejecting the null and indicating that there is a significant heterogeneity in the samples.

Sample age

The ERC samples varied in discernable age from 8 to 105 years old. This age was based on the pith or oldest visible ring. Mean pith date of the samples was 1978.265. Median pith date was

1978. The oldest tree was found at site 73. The mean year of pith (age) for the sampled trees across all 11 sites was 1978 with a standard deviation of 10 years. The trees were divided into groups based upon the standard deviation from the mean (e.g., -2 s.d. =pre-1965, -1 s.d= 1965-1974, within 1 s.d +/-= 1975-1983, +1 s.d=1984-1993, and +2 s.d= post-1994.) The χ^2 test produced a p value < 0.001 thus allowing us to reject the null hypothesis.

Table 2: Chi-square test results for the sample sites

Site No.	66	73	78	89	96	97	121	122	124	127	130
Chi^2	14.25	332.56	39.40	45.04	21.28	31.67	26.58	35.96	14.95	7.60	12.51
df	30	38	39	32	32	29	37	42	25	39	40
Sig.	.993	.000	.452	.063	.925	.335	.898	.732	.942	1.000	1.000

False Ring Totals

The percentage of false rings was highest in the center of the study area, while the lowest percentages of false rings occurred in the westernmost sites [Fig. 9]. False rings as total of annual rings were ranked by dividing the number of sample years with false ring by the total number of sample years (Copenheaver et al. 2010 p.551).

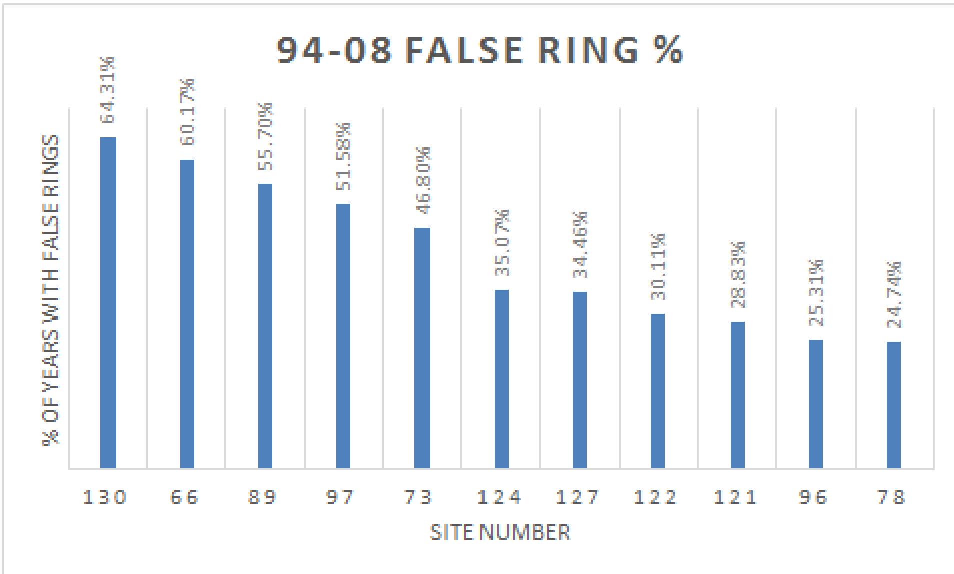

Figure 9: Ranking of total false rings by site

GIS modelling

There is a high degree of positive correlation between the northern sites. There is only a weak or even negative correlation between the northern and southern sites [Fig 10].

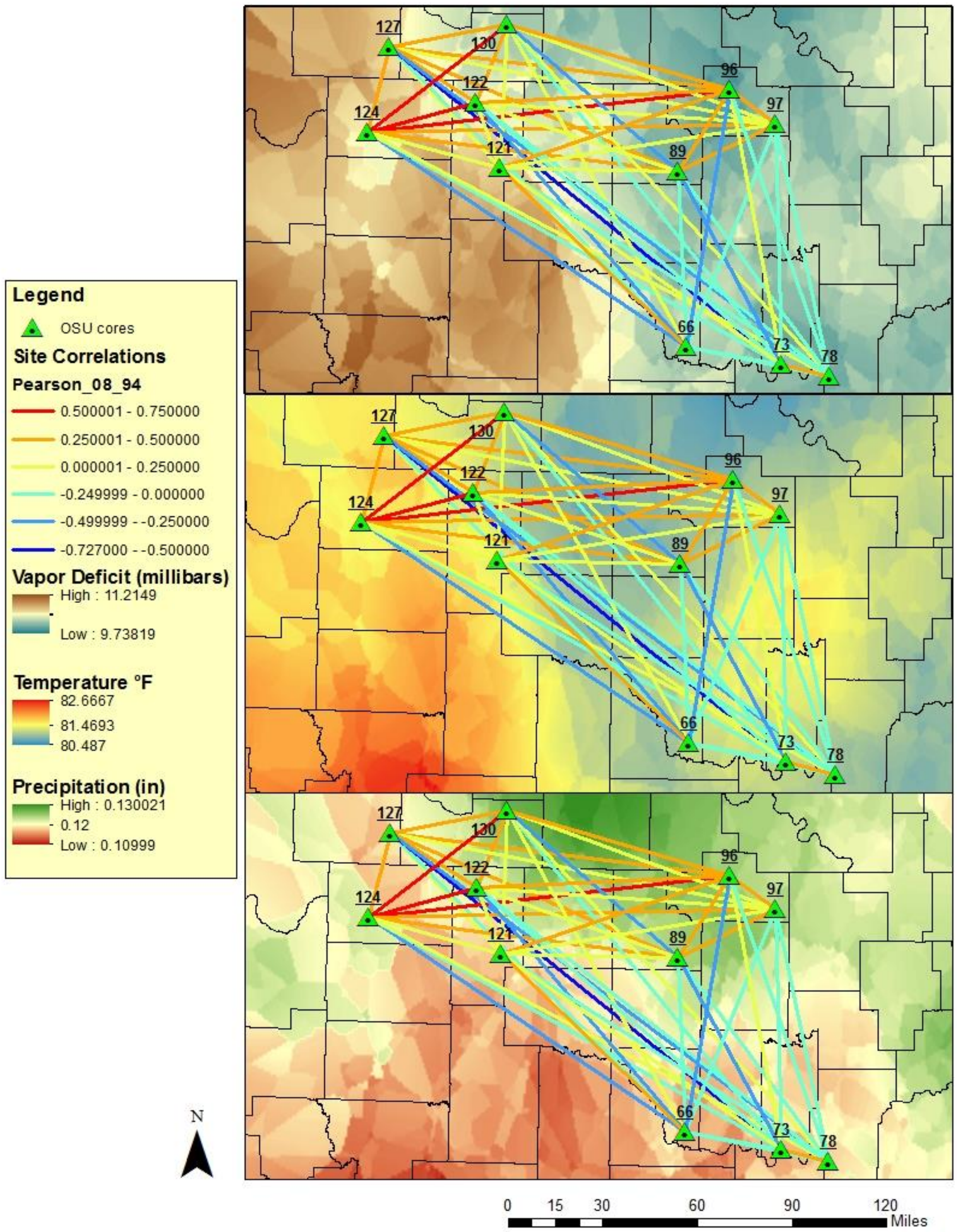

Figure 10: Site correlations compared to 1994 to 2008 average rainfall and average max temperature and 1997 to 2008 vapor deficit

Temperature

Temperatures in the Cross Timbers frequently exceed 100°F in July and August and may drop below freezing in December and January. The highest temperature was 110.77 °F, recorded on 9 September, 2000 in Kingfisher (KING). The warmest year in the study area from 1998 to 2008 was recorded at Bowlegs in 2003. The warmest site in the study area was Bowlegs (BOWL) with an average temperature of 82.6˚F and a maximum monthly average of 94.6˚F. The coolest site was Lahoma (LAHO) with an average of 79.7˚F though the lowest minimum temperature occurred at Byars (BYAR) with a minimum of 63.4˚F.

All study sites show a significant spike in temperature in 2006 and to a lesser extent in 2003 [Fig 11].

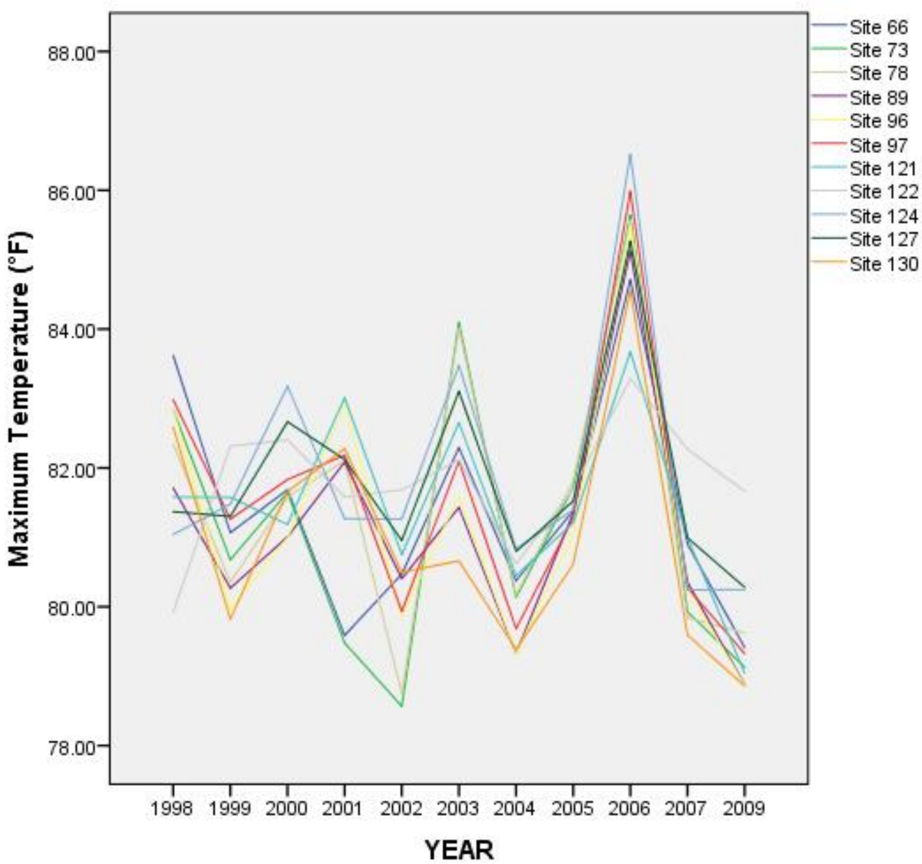

Figure 11: 1997 to 2008 maximum temperature by sample site (°F). Averaged from all Mesonet sites within 30 mi

The driest part of the state during this time period was its southwest corner. All of the sampled sites experienced average growing season temperatures below 81.75 °F but above 80.75°F [Fig 12].

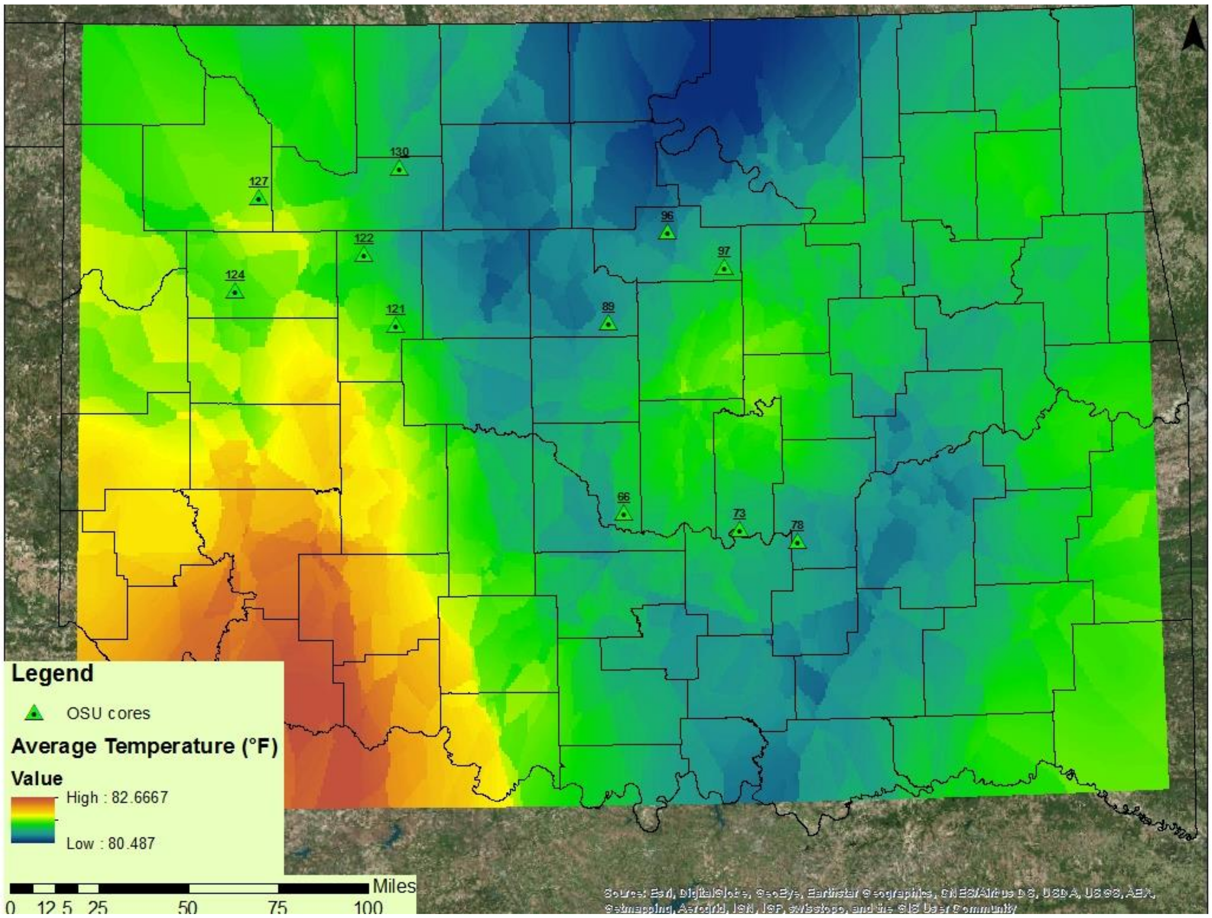

Figure 12: Average maximum growing season temperatures for 1994 and 2008

Rainfall

Rainfall in the Cross Timbers during the 1994-2008 period averages around 23" per year, with wetter weather in the east and dryer in the west [Fig 14]. Oklahoma displays a high spatial variance in rainfall with the western panhandle averaging 17" and the Ouachita Mountains averaging 56" (Oklahoma Climatological Survey 2012). While peak thunderstorm activity occurs in May, precipitation is fairly regular with the exception of dry periods in July and August

(Oklahoma Climatological Survey 2012). The driest year during this period was 2006, and the wettest was either 2007 or 2008 depending on the site [Fig 13].

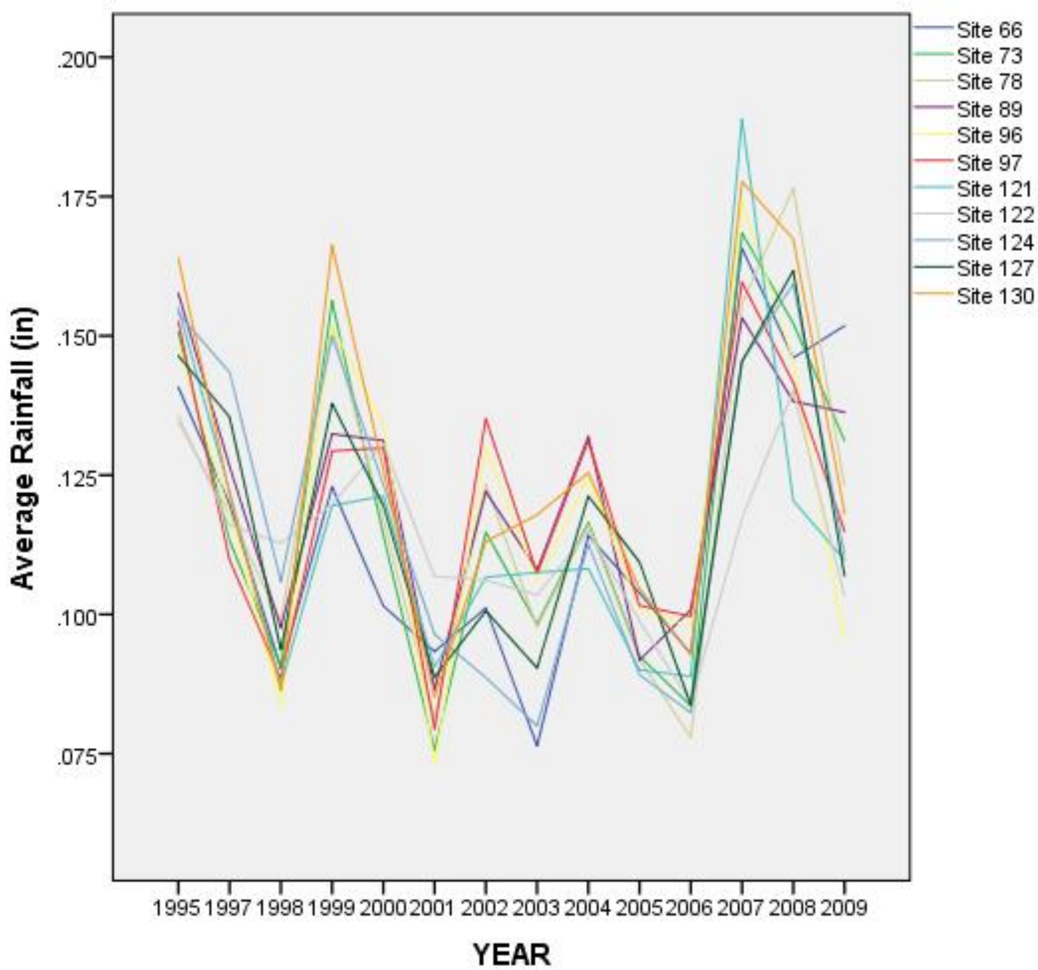

Figure 13: 1995 to 2008 mean rainfall for each sample site (inches). Averaged from all Mesonet stations within 30 mi.

Average precipitation is generally higher in the southeastern corner [Fig 14], but during the period of interest for this study, the highest rainfall was registered in the north central area of the state, near the northernmost sample sites [Fig 15]. It should be noted that figure 14 incorporates snowfall into the total, while the time frame used in figure 15 excludes the winter months when snowfall generally occurs.

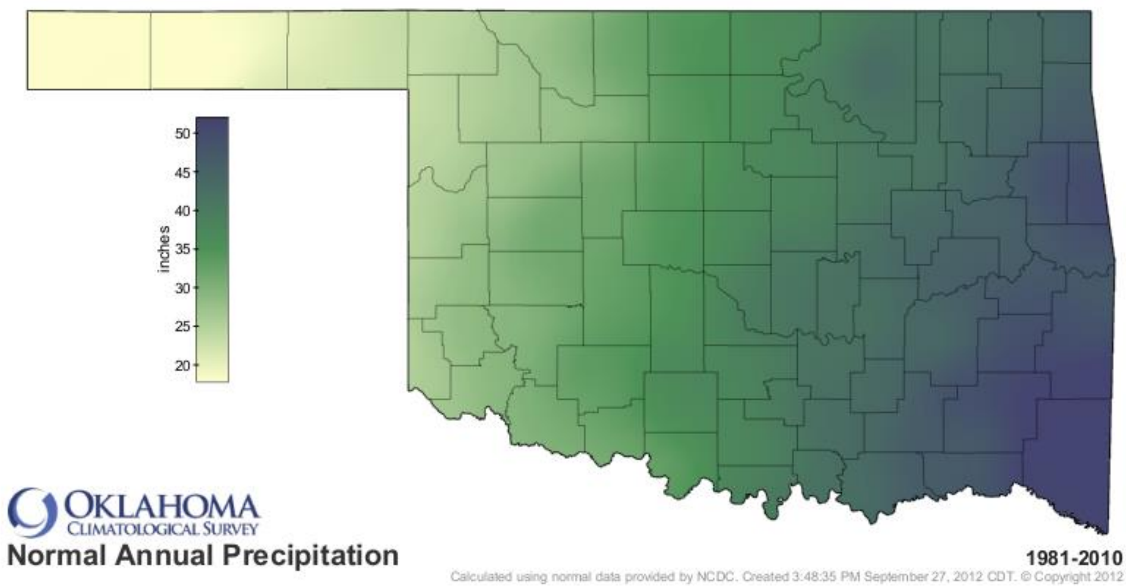

Figure 14: 1981 to 2010 average annual rainfall

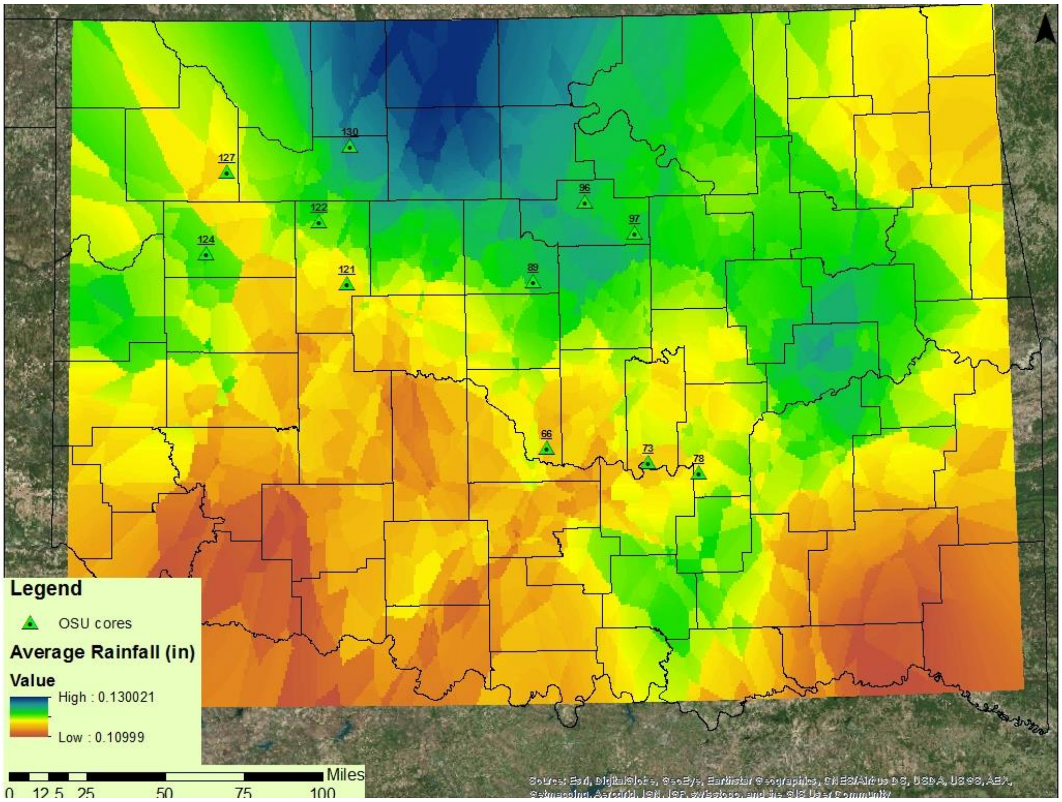

Figure 15: Average growing season precipitation for 1994 to 2008

Evapotranspiration

High temperatures increase evapotranspiration, which increases water stress on a tree, particularly during dry periods. This was measured using average daily vapor deficit, measured in millibars (Mesonet). Mesonet calculates vapor deficit as the difference between the saturation vapor pressure (calculated from air temperature) and the current vapor pressure (calculated from dew point temperature). As with temperature, there is a pronounced peak in 2006 [Fig 16].

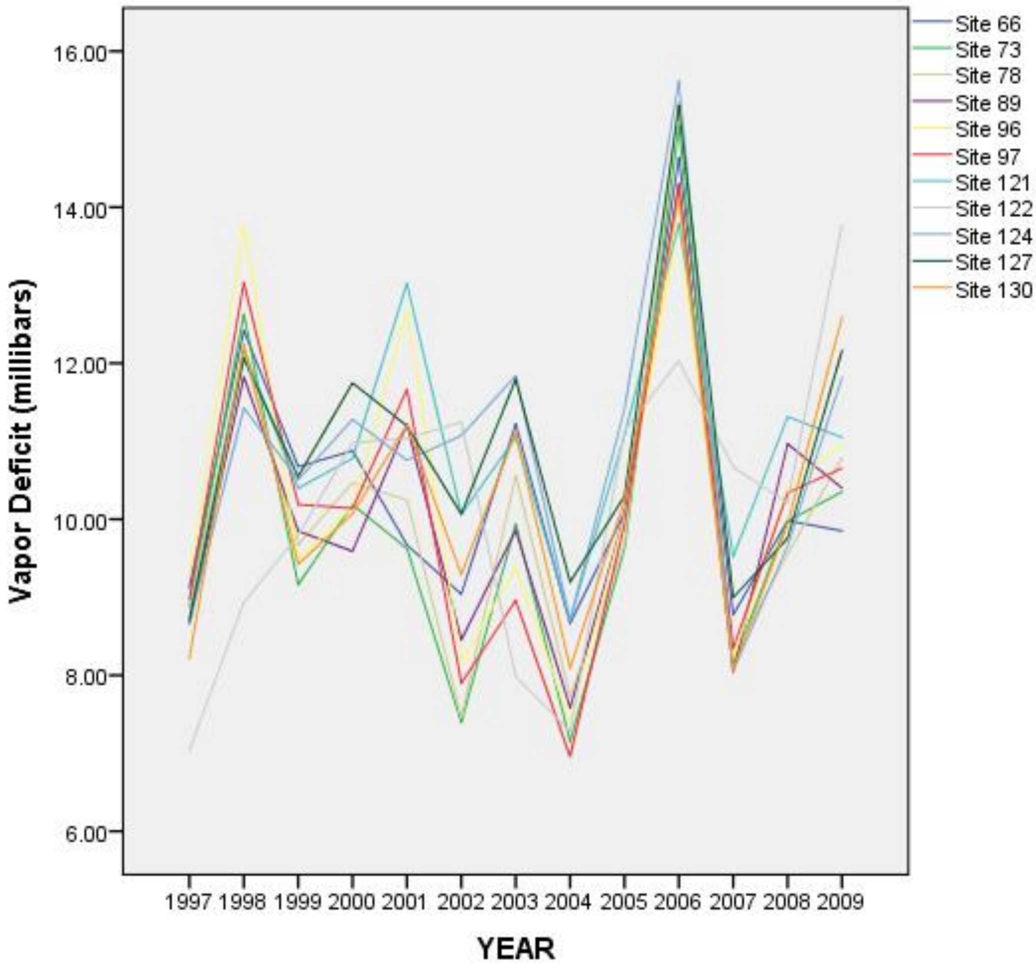

Figure 16: Vapor deficit by sample site (millibars). Averaged from all Mesonet stations within 30 mi

Vapor deficit shows a pronounced difference between the western and eastern study sites [Fig 17]. The western side of the study area was subjected to much higher vapor deficit, suggesting much more severe drought conditions.

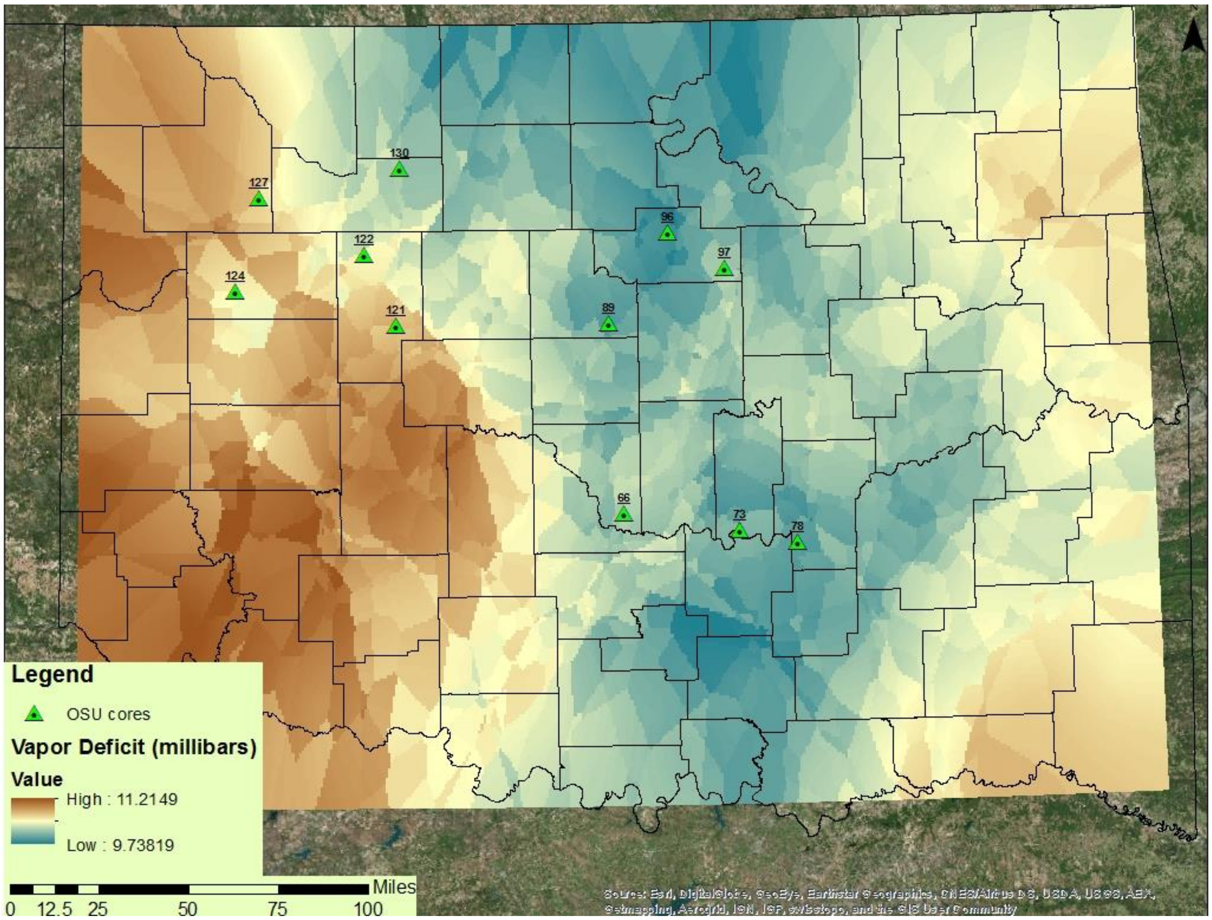

Figure 17: Average vapor deficit during the growing season for 1994 to 2008

Samples v. Climate correlation

The distribution of the sites and their false ring percentages suggests that there is not a linear correlation between false ring occurrence and precipitation totals with moist areas showing sites like 96 and 130 with low and high percentages of false rings and similar patterns in dry areas with sites 121 and 66 [Fig 18].

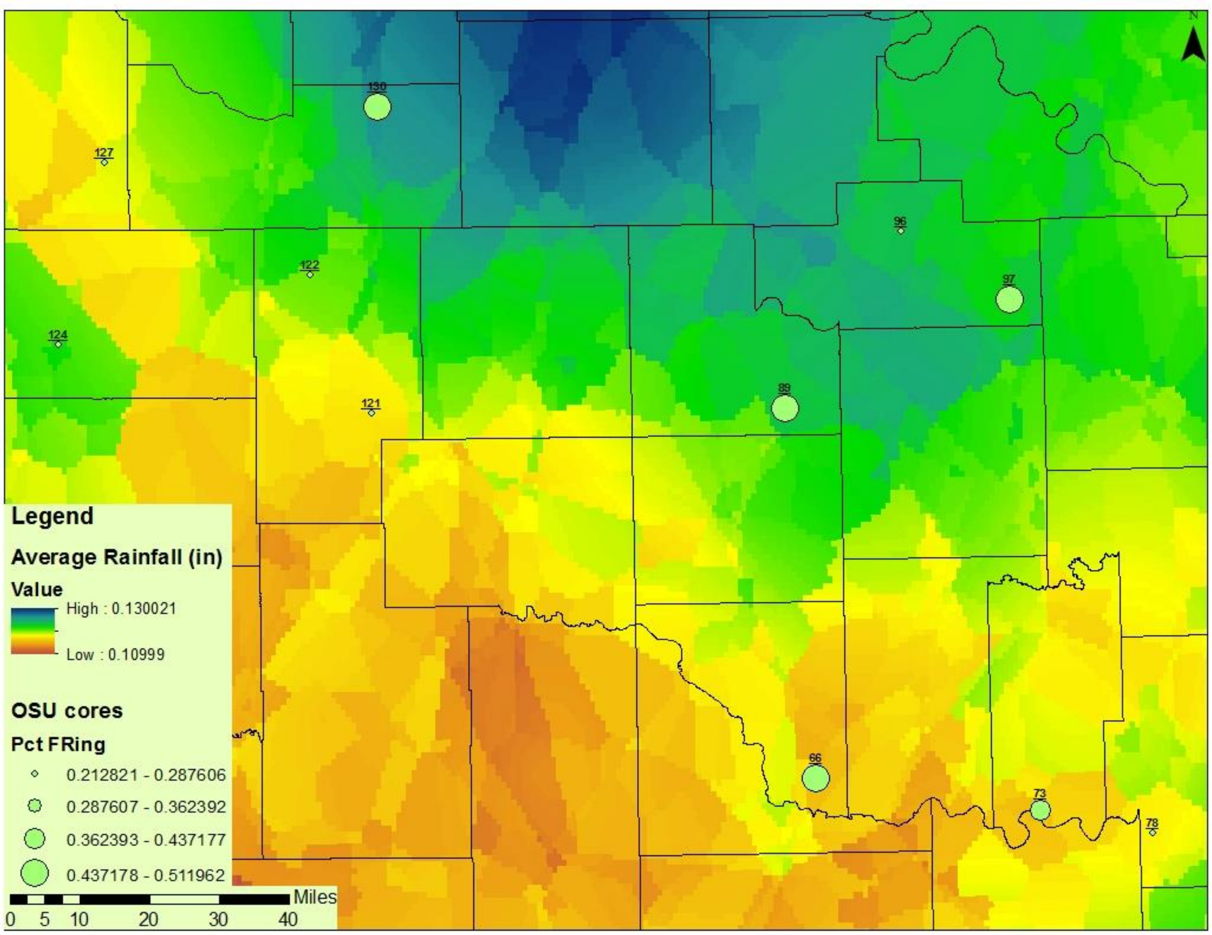

Figure 18: 1994 to 2008 average rainfall compared to % of cores displaying false rings

A plot of the sites sorted by false ring occurrence and temperature shows the lowest number of false rings occurring in the area with exceptionally low/high temperatures [Fig 19].

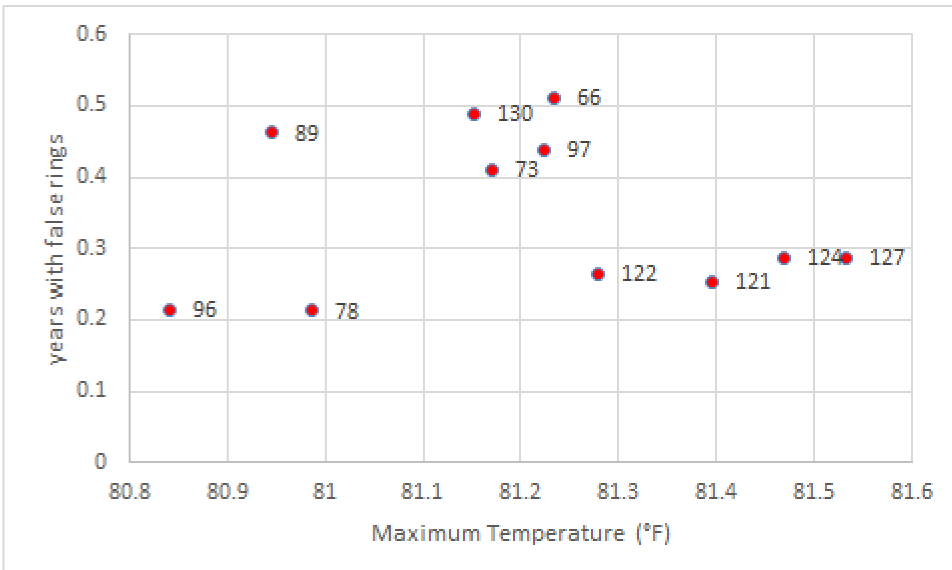

Figure 19: Scatter plot of Maximum Temperature vs. average years with false rings

The comparison between false ring probabilities and temperature suggests a stronger correlation than false rings and precipitation. The sites with the highest and lowest probabilities for false rings appear the areas of lowest average temperature during the growing season [Fig 20]. It is possible that the areas with higher average temperature were subjected to periods of prolonged high temperatures during the growing season. This observation supports trends observed by other authors (Rigling et al. 2002; Camarero et al. 2010; Copenheaver et al. 2010; Edmondson 2010) where false rings increased with variability of climatic conditions.

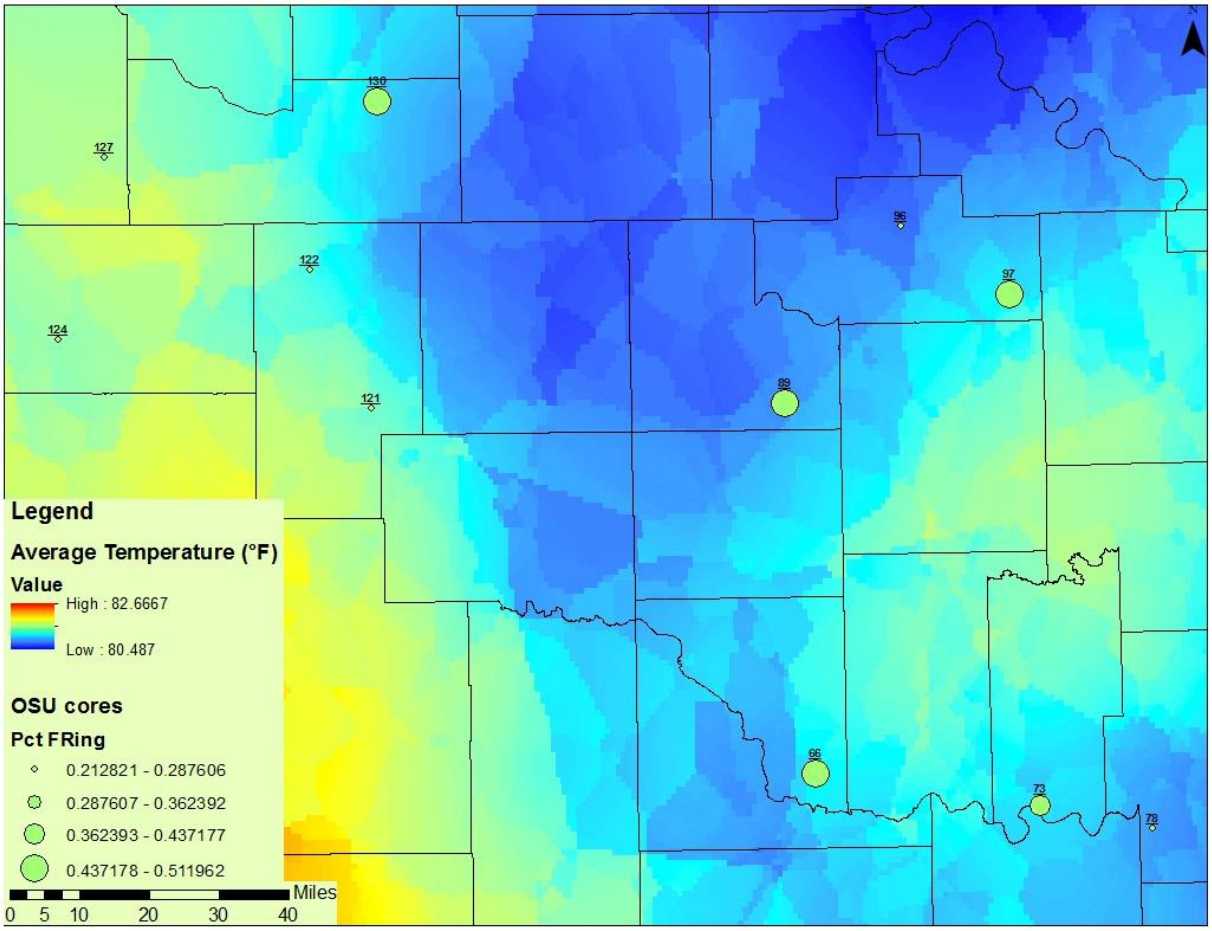

Figure 20: 1997 to 2008 average max temperature compared to % of cores displaying false rings.

Precipitation shows a higher occurrence of false rings in areas with extremely high or low rainfall during the growing season, and low occurrence of false rings in areas with moderate rainfall [Fig 21].

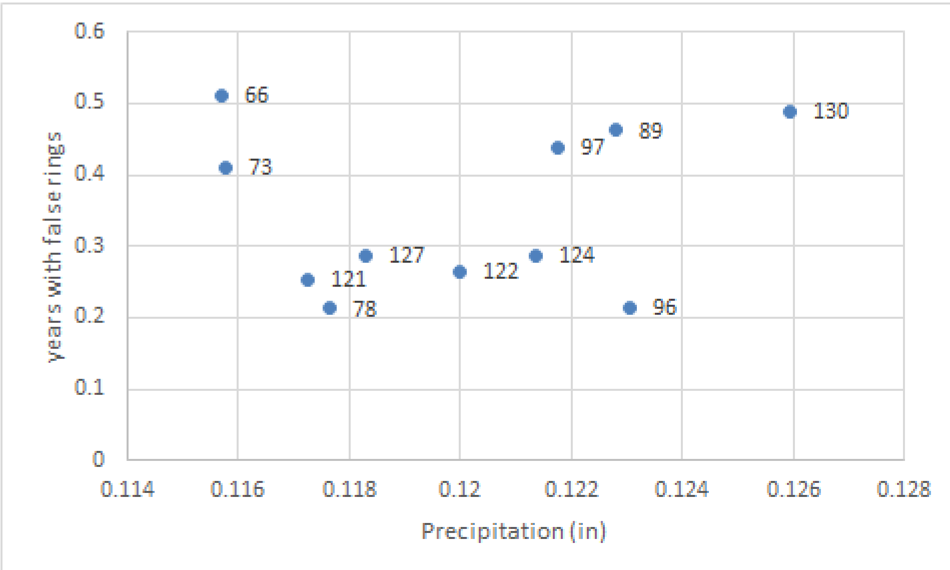

Figure 21: Scatter plot of Precipitation vs. average years with false rings

Vapor deficit shows the strongest spatial correlation with false ring probability and average growing season conditions. There is a noticeably lower total of false rings at the sites subject to high vapor deficit [Fig 21]. This higher occurrence of false rings in areas of mid-range vapor deficit support the conclusion that these areas have been subject to high degrees of variation.

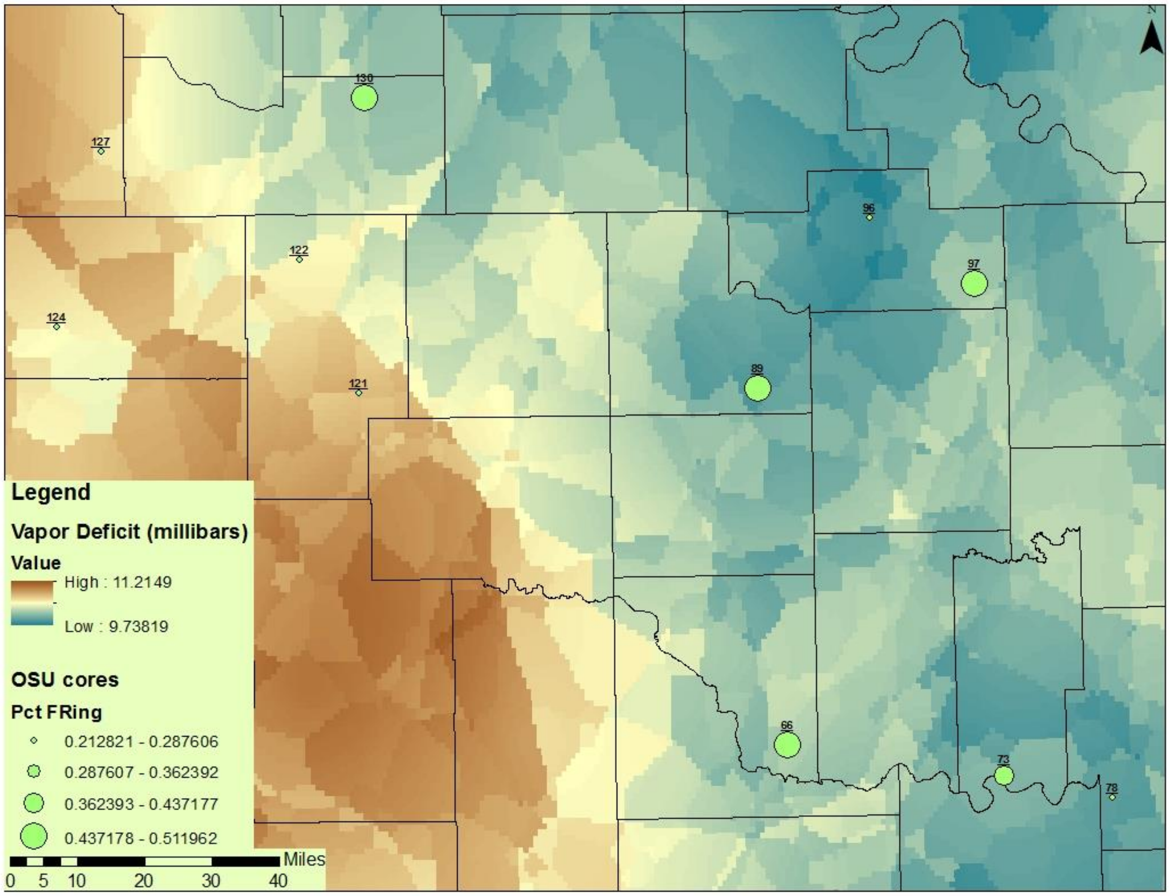

Figure 22: 1997 to 2008 average vapor deficit compared to % of cores displaying false rings

Like temperature, the false rings have lower occurrence at areas of notably high or low vapor deficit, and higher occurrence at moderate levels of vapor deficit [Fig 23].

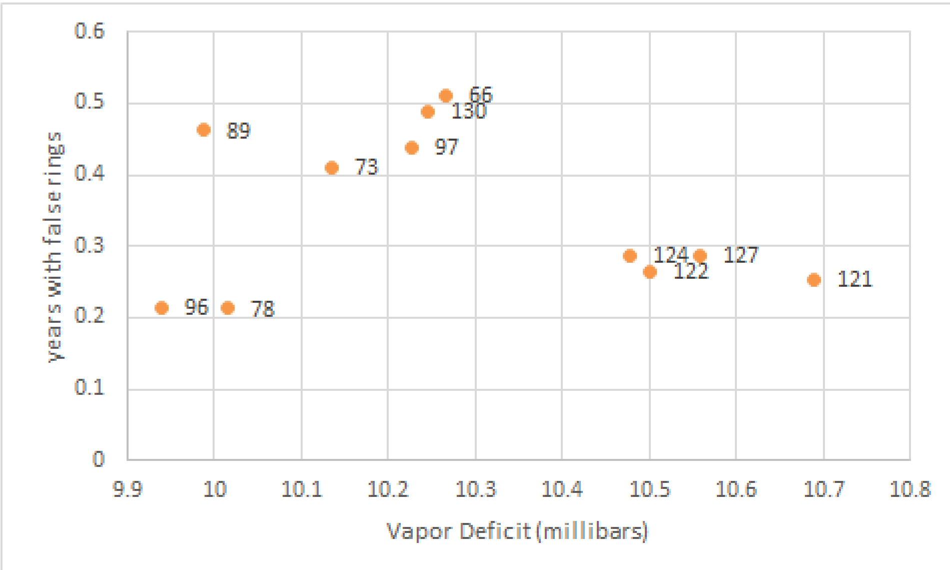

Figure 23: Scatter Plot of Vapor Deficit in millibars vs. average number of years displaying false rings

Spatial Distribution

The strongest correlation of false ring occurrence was between sites 73 and 127 (-72.7%) and had a confidence of 99.8%. The strongest positive correlations all involved site 124 and exceeded 95% confidence. Sites 122 (61.2%), 96 (56.6%), and 130 (56.1%) are all located towards the northern end of the study area [Table 4; Fig 16].

Table 3: Correlation of false ring occurrences between sites for 1994 to 2008

	66	73	78	89	96	97	121	122	124	127	130
66	1	-.059	-.120	-.040	-.316	-.032	.369	-.329	-.409	-.045	.022
73		1	.290	-.331	.079	-.043	.151	-.211	-.024	-.727	-.121
78			1	-.129	-.233	-.182	-.242	-.072	.197	-.282	.172
89				1	.437	.341	.065	.142	.376	.455	-.040
96					1	.391	.471	.315	.566	.406	.412
97						1	.097	.167	.274	.075	.043
121							1	.031	.040	.070	.211
122								1	.612	.278	.306
124									1	.404	.561
127										1	.397
130											1

Latitude/Longitude

The sites display a strong degree of positive correlation based on the latitude of the site. The highest correlations occur between sites at the northern end of the study area, while the weakest occur between northern and southern sites [Fig 10, Table 4]. This trend appears in both the 1984-2008 series and the 1994-2008 series of correlations. This suggests that there is an underlying spatial factor influencing the occurrence of false rings in ERC.

CHAPTER V

DISCUSSION & CONCLUSIONS

The false rings in the cores from the ERC samples show a stronger correlation to vapor deficit than temperature or precipitation. The western part of the study area showed limited number of false rings while the percentage of false rings was highest in the center of the study area. Scatterplots show a curvilinear trend in false rings that appears strongest with vapor deficit. Based on this spatial distribution and previous research (Copenheaver et al. 2006; Copenheaver et al. 2010; Edmondson 2010) false rings are representative of average but highly variable water stress.

Observed Patterns

False rings appear less frequently in areas of extreme temperature and vapor deficit. This supports the theory that false rings are the result of variability in local atmospheric phenomena. The sites with high percentages of false rings occur east of the boundary between moderate and high vapor deficit, while areas west of the boundary show low occurrences of false rings [Fig 21].

Weather Inferences

The strongest numerical correlations in false ring probability was moderate vapor deficit. At this scale drought and false rings do not appear to have a strong correlation. False rings seem more common in areas where the rainfall is in the middle of the range for the state. The occurrence of false rings appears to correlate to the variability of precipitation.

The spatial distribution of false rings suggests that areas of consistently wet or dry conditions are less prone to false ring formation. Areas with high degree of vapor deficit have relatively low probability of false rings, while areas of moderate to low vapor deficit form more false rings. These area of low vapor deficit are linked, but not synonymous, with precipitation and temperature. Vapor deficit represents the combination of temperature and humidity that promotes evaporation. As the vapor deficit increases, the trees will transpire more. The scatter plots comparing false rings to each atmospheric variable suggest a curvilinear correlation, with temperature and vapor deficit producing fewer false rings at the extreme high and low ends of the scale while extremely high/low precipitation produces more false rings. This discord between the precipitation maps and scatter plots may be due to the tendency for the Cross Timbers to receive a majority of annual precipitation during large infrequent thunderstorms rather than consistent light rainfall. More investigation at different time scales is necessary.

Future Research

The use of archived samples in this study leaves uncertainty regarding the influence of microclimate on false rings, due to gaps in the metadata. Copenheaver et al. (2005) demonstrated that the location of a particular tree relative to other specimens in the stand can affect the growth of the tree. Therefore, a follow up study using primary samples with associated location data is desirable. Additionally, this study could be supplemented with samples from the high rainfall areas in Garfield and Grant counties. Adding ERC from other sites to obtain an adequate sample size to use more powerful statistical analyses methodology such as regression analysis or p-test or ANOVA, etc.

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APPENDICES

Site	Elevation (m)	UTM E	UTM N	Region
66	337	662430.12	3875569.19	South Central
73	283	714128.52	3868055.27	South Central
78	277	740023.25	3862987.94	South Central
89	338	655473.60	3960852.00	North Central
96	301	682027.48	4001657.22	North Central
97	267	707251.57	3985995.03	North Central
121	460	559845.98	3959764.72	North West
122	498	545782.68	3991712.85	North West
124	624	487814.30	3975592.60	North West
127	576	498296.58	4017473.33	North West
130	422	561188.61	4030296.26	North West

Location data of sample sites. Provided by Dr. Ryan DeSantis (personal communication)

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