

AN EVALUATION OF HISTORICAL FIRE OCCURRENCE, DROUGHT, AND THE  
EL NIÑO SOUTHERN OSCILLATION IN THE GREATER CROSS TIMBERS  
REGION, U.S.A.

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A Thesis  
presented to  
the Faculty of the Graduate School  
at the University of Missouri-Columbia

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In Partial Fulfillment  
of the Requirements for the Degree  
Master of Science

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by  
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MAY 2017

The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled  
AN EVALUATION OF HISTORICAL FIRE OCCURRENCE, DROUGHT, AND THE  
EL NIÑO SOUTHERN OSCILLATION IN THE GREATER CROSS TIMBERS  
REGION, U.S.A

presented by Molly Rooney,

a candidate for the degree of Master of Science,

and hereby certify that, in their opinion, it is worthy of acceptance.

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## **DEDICATION**

The pursuit of my Master's education would not have been possible without the support of my family and friends. My parents have been nothing but supportive throughout my education, and even dutifully called me every week while I was living in Ghana for two years. Missouri has been closer, but not without challenges. Thank you mom and dad for your kind words, encouragement, and good faith that I would finish my education and decide what I want to do when I "grow up." Thank you for patiently explaining my research to your friends, even if you were not sure what exactly it was. Your encouragement helped me stay positive throughout my education, and motivated to do my best every day as a person and as a student. And thank you to my brother, Ben, who has endured graduate school alongside me, albeit in sunny San Diego. Thank you for making me laugh and sharing your graduate struggles with me- it has offered me perspective.

Thank you to my many friends all over the country and in Columbia who withstood my graduate frugality, my discussions of tree rings, my frustrations with ticks, and my fluctuating time management during my education. Knowing I have your support near and far has helped to keep me grounded, and motivated me to produce work I feel proud to share with you all. Thank you for allowing me to stay your "friend who loves trees." And thank you to Spencer, who has withstood countless hours of giddy sharing of research, driving between major Missouri cities, confused statistical analysis, and frazzled pizza eating over these two years. Y'all- we made it!

## ACKNOWLEDGEMENTS

My research would not have been possible without the support and funding from the U.S. Fish and Wildlife Service. Staff enthusiasm, cooperation, and support during field work made the work both enjoyable and engaging. A special thanks to Joe Marshall for countless hours in the field and in the laboratory, providing feedback and moral support. Additional gratitude to Dr. Richard Guyette, for providing mentorship, inspiration, and perspective on dendrochronology. Additional thanks to the field and laboratory technicians Abbey Kestermont and Sam Kosark, for smiling through countless hours in the field and the laboratory, and for your excitement surrounding dendrochronology.

Thank you to the Department of Natural Resources staff and students for supporting me over the course of my studies. Thank you also to my fellow graduate students for joining in long hours of work, laughter and engaging conversation. A special debt of gratitude is owed to my lab mate, Mary Short. Thank you for listening to my ideas, failings, and successes over two years together.

A gracious thank you to my adviser, Dr. Michael Stambaugh for introducing me to dendrochronology, and for sharing your enthusiasm for tree rings, fire, and learning with me each day. Thank you for your guidance in my education, and for helping me through my studies. A final thank you to my entire committee, Drs. Muzika and Lupo for offering mentorship and goodwill throughout my program. Your guidance was instrumental to my success at Mizzou.

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ABSTRACT

A concern over wildfire occurrence, and its relationship to drought and a changing climate has brought increased focus to the interface between the public and fire. Multiple factors, including an increase in fuel loading from decades of continuous fire suppression, changes in land use and ownership, and management strategies, are dampening the success of wildfire suppression rates in some ecosystems. Wildfire occurrence is influenced by many factors ranging from drought and climate oscillations at the regional level to fuel availability and land-use at the site level. This study evaluates and explores the extent, frequency, seasonality, and severity of fires across the Cross Timbers, and through time. Historical fire events were reconstructed at three new study sites in unrepresented geographic locations. Fire event chronologies were developed from fire scars spanning three centuries. These chronologies were compared with data from ten existing sites to evaluate fire regime characteristics and changes at a regional scale. Findings suggest that, while fire frequency has increased following European-American Settlement, fire severity has trended downward. Site differences in fire occurrence exist across the greater Cross Timbers region. The results of this study

indicate a prevalence of dormant season fire across the greater Cross Timbers region. Fire events were 2-7 times more frequent when considered at a regional scale.

Some of the strongest ENSO signals yet detected in any tree-ring data worldwide are in post oak chronologies of Texas and Oklahoma. Little is known about how the role of climate differs in driving fire occurrence at the site to regional scale. In this region, many studies have attempted to explore how climate drives fire at the site level, but inconsistencies in the results of these studies leave questions about the comparability of these conclusions, and the role of climate in altering climate activity at the regional scale. This study assessed the relationship between climate patterns on fire occurrence in the southcentral U.S. and evaluated the independent and interactive influences of drought and the ENSO on fire occurrences at both site and regional levels. The relationship between fire occurrence and drought was largely unclear at the site scale, but drought was found to be a significant driver of fire synchrony at the regional scale. Drier than expected conditions were observed in the year of fire events at the regional level. This relationship was less apparent in the post-European-American Settlement period.

## INTRODUCTION

This thesis is composed of three chapters. The first chapter offers a literature review of relevant data and publications that are related to the historical role of fire in the greater Cross Timbers region of Oklahoma and Texas, U.S.A. This chapter highlights the composition of the Cross Timbers ecoregion, existing knowledge about the role of fire across the landscape, and known interactions between climate and fire in the U.S. This chapter is meant to familiarize the reader with the Cross Timbers ecoregion, and offer understanding and motivation for the study.

The second chapter explores the historical role of fire in the greater Cross Timbers region using thirteen fire history reconstructions of fire occurrence in Oklahoma and Texas. The goal of this study is to evaluate and explore the extent, frequency, seasonality, and severity of fires across the Cross Timbers, and through time. Three new datasets are added to ten existing fire history records to examine how fire occurrence has changed over the last three centuries. Fire occurrence was examined at two scales: at the site level and at the regional level, where the role of fire across the region was considered.

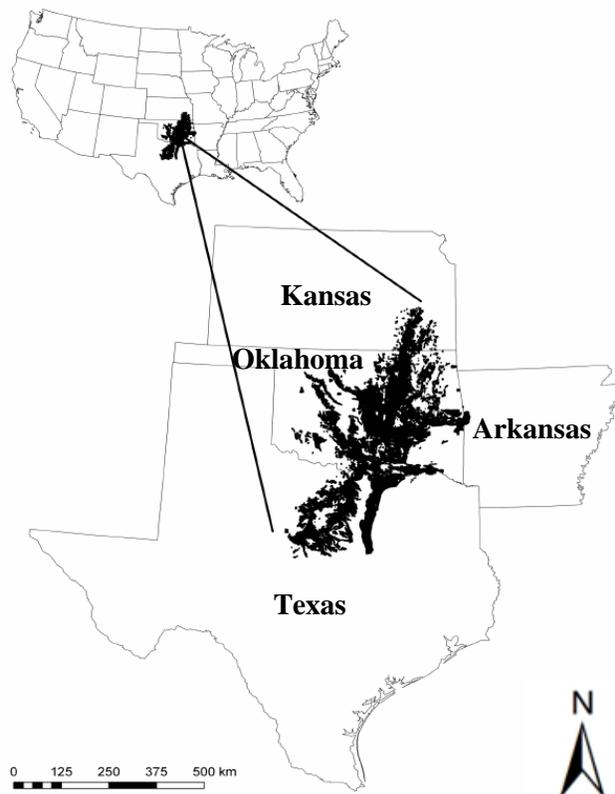
The goal of the third chapter was to assess the relationship between climate patterns on fire occurrence in the southcentral region of the United States. The study evaluates the independent and interactive influences of drought and the El Niño Southern Oscillation (ENSO) on fire occurrences at both site and regional level. The geographic relationship between fire history sites is considered, and recent climate and fire data is utilized to extend our understanding of the relationship between climate and fire in the greater Cross Timbers region of the U.S.

## CHAPTER ONE: LITERATURE REVIEW

### 1. Characteristics of the Cross Timbers

The Cross Timbers ecoregion in southcentral North America is a patchwork of forest, savanna, and prairie, dominated by post oak (*Quercus stellata*) and blackjack oak (*Quercus marilandica*; Duck and Fletcher 1943, Rice and Penfound 1959, Hoagland et al. 1999). The origin of the term ‘Cross Timbers’ is unknown, but the name describes a forest region and may have originated when early settlers travelling West had to cross successive bands of open prairie and dense upland woodlands and forests (Kuchler 1964). The region is distinguished by mixed-grass prairies and oak woodlands, and prevails between the eastern deciduous forest and Great Plains prairie ecosystems (Figure 1, Kuchler 1964). The vegetation of the Cross Timbers persevere largely because this ancient forest formation has not experienced large-scale industrial logging as the Cross Timbers tend to be found on steep and/or infertile terrain that limit their economic value (Therrell and Stahle 1998). Low relief and low elevation characterize the Cross Timbers, with elevations ranging from a low of approximately 150 m along the Red River to a high of 755 m in the Wichita Mountains (Johnson 2006). Ridges in the region are formed by resistant sandstone, and the formations’ susceptibility to erosion often results in low rolling hills and broad flat valleys, with a maximum relief of approximately 180 m (Johnson 2006). In addition to topography, the soils appear to be a determining factor of the distribution of the Cross Timbers. The upland Cross Timbers are confined to coarse textured soils from sandstone parent material, while grasslands tend to dominate the finer textured soils of this region (Bruner 1931, Dyksterhuis 1948, Rice and Penfound 1959). The post oaks that dominate the canopy rarely exceed 15 m in height and 60 cm in

diameter, but can live for hundreds of years. Consequently, much of the Cross Timbers' forests have thus not been extensively logged or farmed as much as the eastern deciduous forests, and subsequently, the Cross Timbers may contain some of the largest tracts of pre-settlement forests in the eastern United States (Stahle and Hehr 1984, Stahle and Chaney 1994, Therrell and Stahle 1998).



**Figure 1.** Map of the Cross Timbers ecoregion derived from Kuchler (1964).

The Cross Timbers is described by gradients in both precipitation and temperature. The Cross Timbers run in a generally North-South direction across 72337 square kilometers that includes portions of southern Kansas, eastern Oklahoma, western Arkansas, and north central Texas. Annual temperatures range from 15°C in the northernmost region to 18.8°C in the south. Average annual precipitation varies from 102 cm in

the east to 71 cm in the west (Hoagland et al. 1999). Precipitation is well distributed throughout the year with a maximum in May. Wide swings in precipitation can result in severe droughts across the region (Arndt 2011).

Severe drought has been categorized as the greatest recurring natural disaster in North America (Cook et al. 2007). In the Cross Timbers, drought occurs at approximately 20-year intervals (Stahle and Hehr 1984, Therrell and Stahle 1998, Clark 2003). Extended droughts have been a consistent feature of the southcentral climate since at least the 9<sup>th</sup> century (Cleaveland et al. 2011). Stahle and Hehr (1984) demonstrated that chronologies of Post Oak show more sensitivity to climate westward toward the prairie boarder- consistent with decreased rainfall, forest cover, species diversity, and overall tree size. These findings underscore the implications of declining rainfall in the Southcentral United States.

## **2. Fire History in the Cross Timbers**

Fire has occurred in the Cross Timbers area for at least 5000 years (Albert 1981; Bryant and Holloway 1985; Anderson 2006). Although expanses of old-growth forests exist in the Cross Timbers, the forests have been affected by changes in fire frequency and the advent of grazing since the beginning of the 20<sup>th</sup> century (Rice and Penfound 1959, Wyckoff 1984, Stambaugh et al. 2014). The potential vegetation of the Cross Timbers region was defined and mapped by Kuchler (1964, Figure 1) and was thought to support understory fires with a return interval of 1 to 10 years (Brown 2000). In many places in the Cross Timbers, now closed-canopy forests were previously inhabited by oak savannas. This change has occurred for a number of reasons, including both fire

suppression and grazing by domesticated animals (Bruner 1931, Dyksterhuis 1948, Johnson and Risser 1975, Abrams 1992, Clark 2003).

At the Keystone Ancient Forest Preserve (KAFP), fires were found to occur approximately every two years, with larger-scale fire events occurring ever 8.5 years (Clark et al. 2007). Fires were found to be more frequent at this site following Oklahoma statehood and European American Settlement (EAS), and the increase in fire in this period was attributed to increasing anthropogenic ignitions following statehood. At the KAFP, there was a concurrence of both moderate and large-scale fire events within the site during periods of below normal Palmer Drought Severity Index (PDSI) values (Clark 2007). At the Okmulgee Game Management Area (GMA), there was an increase observed in fire between the eighteenth and twenty-first centuries, attributed to changes in human occupation in the area- and emphasizing the role of anthropogenic ignition in the fire regime (DeSantis et al. 2010). At Tallgrass Prairie Preserve, fire occurrence increased following EAS, and the site was found to have experienced no recent fire suppression or exclusion, although changes in fire frequency did reflect transitions in land use (Allen et al. 2011). At the Nickel Family Nature and Wildlife Preserve, the fire regime appeared to be influenced by human culture and drought (Stambaugh et al. 2013). Fire was more frequent following the immigration of native peoples into northeast Oklahoma, but considerably less frequent due to fire suppression after 1925 (Stambaugh et al. 2013). At the Wichita Mountains National Wildlife Refuge (NWR), fire occurrence decreased following EAS, and decreased fire occurrence in the twentieth century has led to the encroachment of eastern redcedar (*Juniperus virginiana*) at the refuge. At Purtil Creek State Park in northern Texas, findings showed that fire had decreased through

time, and the fire regime had been influenced by humans (Stambaugh et al. 2011). At Bastrop State Park in southcentral Texas, historical fire frequency was lower following the EAS period, and fire occurrence characteristics were observed to correspond with local and regional changes in land use (Stambaugh et al. 2017).

In some areas of the Cross Timbers, fire occurrence has increased since European-American settlement (Clark et al. 2007, DeSantis et al. 2010, Allen et al. 2011), and in other areas it has decreased (Stambaugh et al. 2008, Stambaugh et al. 2011, Stambaugh et al. 2017). These contrasting fire regime changes may indicate that fire suppression has been spatially variable. In the Missouri Ozarks, Guyette et al. (2002) investigated fire occurrence prior to and after European-American settlement. Here, in vegetation types similar to the Cross Timbers, the frequency of fires increased after European-American settlement because settlers utilized fire for many of the same purposes as the Native Americans. Fire occurrence did not decrease until there was a substantial increase in human population in the 20<sup>th</sup> century to bring an end to fire use to protect property (Guyette et al. 2002).

The fire regime that characterizes the Cross Timbers is of low intensity, rarely killing trees larger than 5 cm DBH, and are typically not stand-replacing events (Burton et al. 2010). Climate has been a contributing factor to fire ignition and spread throughout forested regions of eastern North America by influencing surface fuel production and fuel conditioning (Bergeron 1991, Guyette and Cutter 1991). In combination with climate, topographic conditions are also related to fire frequency and spread (Pyne et al 1996, Guyette and Dey 2000). The majority of fires are less frequent on sites with increased

fuel moisture and are less likely to spread over topo-geographically “rough” areas (Pyne 1996, Guyette and Dey 2000).

### **3. Forest Stand Dynamics and Vegetation Change in the Cross Timbers**

In addition to fire, the Cross Timbers region has been influenced by a number of other natural disturbances, including grazing, wind events, drought, tornados, and ice that can kill or maim large branches, single trees, or large groups of trees (Clark 2003).

Tornados, which can create large disturbances in the forest stands of the Cross Timbers, are rare and have a return interval of approximately 2000 years (NOAA 2011). Although some canopy trees are considered to be relatively intolerant of shade, there is evidence of continuous replacement of canopy trees by growth of understory saplings into the canopy without gaps (Clark et al. 2005, Karki 2007). Small canopy gaps can facilitate growth of saplings into the canopy (Karki 2007).

Tree growth in the Cross Timbers is typically very slow due in part to the relatively low rainfall in this marginal climate zone and because Cross Timbers soils tend to be low in natural fertility. The Cross Timbers’ tree species are particularly sensitive to climate, producing narrow rings (Stahle and Hehr 1984), and exhibiting high mortality during severe droughts like that of the 1950s (Rice and Penfound 1959).

Dendrochronological studies have shown evidence of an increase in eastern redcedar recruitment and a decline in oak recruitment since the 1970s from the combined effects of fire suppression and oak drought mortality (DeSantis et al. 2011, Stambaugh et al. 2009, Stambaugh et al. 2014). Regional mortality of canopy species such as blackjack oak following the 1950s drought (Rice and Penfound 1959, DeSantis 2011, Hammer

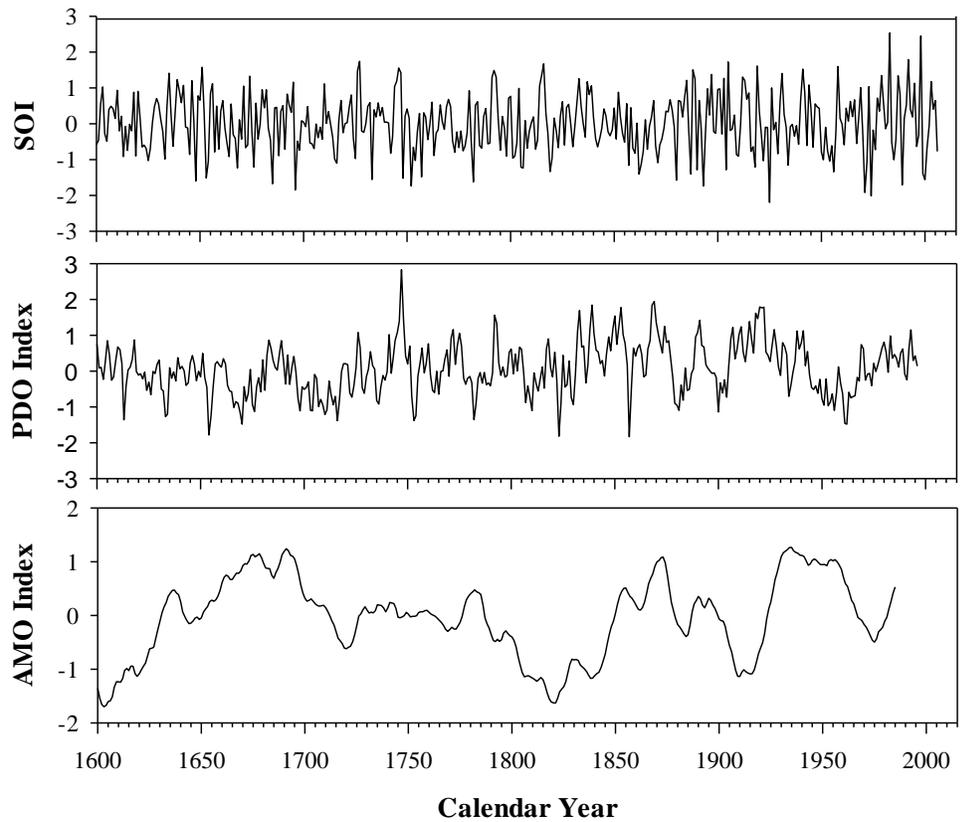
2012) opened stands for recruitment of new cohorts of trees. Fire suppression reduced the control on eastern redcedar encroachment and ended the stimulation of oak sprouting (Rice and Penfound 1959). Eastern redcedar has historically been a minor component in riparian zones, rocky outcrops and cliffs where fire burned infrequently. It is disseminated widely and effectively by birds (Holthuijzen and Sharik 1984, Holthuijzen et al. 1986) and cannot tolerate fire when small (Engle and Stritzke 1995).

The dominance of both post oak and blackjack oak is well-documented in the Cross Timbers. A study of Oklahoma's forests in the 1950s found these species to be the most vital on a statewide basis in terms of presence, frequency, density, and basal area (Rice and Penfound 1959). A re-measurement in the 2000s of 30 of the 208 original Rice and Penfound plots showed that post oak was still the most important canopy tree across the state, but that the relative density of post oak and blackjack oak saplings decreased by nearly two-thirds across the Cross Timbers (DeSantis and Hallgren 2011). Replacement species included eastern redcedar in the western Cross Timbers and winged elm (*Ulmus alata*) and black hickory (*Carya texana*) in the eastern Cross Timbers (Desantis et al. 2010). The regeneration of dominant oaks and blackjack oak is historically related to fire. Although successful reproduction by seedlings is very rare (Backoulou 1998, Clark and Hallgren 2003, Desantis and Hallgren 2011), these species re-sprout prolifically. Both oak species can be characterized as auto-accumulating, as there can be four or more cohorts of reproduction that accumulate over a few decades (Clark and Hallgren 2003, Johnson 1993).

## **4. Climate Variability Affecting Fire Occurrence**

### **4.1 El-Nino- Southern Oscillation (ENSO)**

The El Niño Southern Oscillation (ENSO) is an aperiodic phenomenon that reoccurs every 2-7 years, and manifested in two different phases: The El Niño, and the La Niña. Once a phase begins (either El Niño or the La Niña), it persists for 18-24 months (Philander 1985, Yasunari 1985, Allan et al. 1996). Although the climatic patterns that drive either the La Niña or the El Niño are often opposite, each El Niño or La Niña varies in its behavior (i.e. duration, extent) (Ropelewski and Halpert 1987, Kiladis and Diaz 1989, Allen et al. 1996). During El Niño events, warming of the tropical regions of the Pacific and Indian Oceans displaces the rainfall-producing systems from the continents to these ocean regions, altering climatic regimes. During La Niña events, the opposite movement occurs, cooling the tropical regions of the Pacific and Indian Oceans (Webster 1994, Allen et al. 1996). In general, La Niña events cause dry conditions in the southwestern U.S. (Trenberth et al. 1988, D'Arrigo and Jacoby 1991, Westerling and Swetnam 2003). During these events, colder ocean waters are present in the tropical Pacific due to strengthening trade winds. This process encumbers rainfall, bringing dry conditions to the southwestern United States, including the Cross Timbers region of Oklahoma and Texas (Cook et al. 2000). In contrast, El Niño events have an association with increased moisture. Some of the strongest ENSO signals yet detected in any tree-ring data worldwide are in post oak chronologies of Texas and Oklahoma (Turney 2003).



**Figure 2.** Reconstructions of (A) the Southern Oscillation Index (SOI, Cook et al. 2008) (B) the Pacific Decadal Oscillation (PDO, MacDonald and Case 2006) and the (C) Atlantic Multi-Decadal Oscillation (AMO, Gray 2004) since 1600 C.E.

A common way that the conditions and effects of ENSO events are quantified is the Southern Oscillation Index (SOI, Figure 2). The SOI is computed as the difference in standardized Sea Level Pressures (SLPs) measured between Tahiti and Darwin, Australia, and is a measure of the atmosphere over the tropical Pacific. When the SOI is in its positive state, easterly winds are strong in the tropics, and the tropical Pacific is usually observing a La Niña state. When the SOI is negative, easterly winds are weak and the tropical Pacific is usually observing an El Niño state, and unusually warm SSTs along the equator (Ropelewski and Halpert 1986).

Swetnam and Betancourt (1990) demonstrated the relationship between fire activity and ENSO variability in the southwestern United States by highlighting the finding that the area burned in a wildfire event was related to spring conditions of that year that coincided with the warm or cool phase of ENSO. Since this study, relationships between ENSO related droughts have been established by other studies in the U.S (Trenberth et al. 1988, D'Arrigo and Jacoby 1991, Grissino-Mayer and Swetnam 2000, Westerling and Swetnam 2003).

#### **4.2 Pacific Decadal Oscillation**

The Pacific Decadal Oscillation (PDO, Figure 2) functions over a decadal time scale with a periodicity of approximately 20 to 40 years (Ghil and Vautard 1991, Mantua et al. 1997). Gedalof and Smith (2001) used tree-ring reconstructions to reproduce and investigate historical variations in the PDO. In this study, the PDO was observed to have shifted eleven times since 1650 between the warm and cool phase, and to have an average period of 23 years. The positive, or warm phase of the PDO coincides with cooler SSTs in the central Pacific with anomalously warmer SSTs along North America's western coast (Mantua and Hare 2002, Sheppard et al. 2002). The negative, or cool phase of PDO occurs when SSTs are warmer in the central Pacific and cooler along the western coast of North America (Mantua and Hare 2002, MacDonald and Case 2005). Mantua and Hare (2002) show that the PDO is not oscillatory, but instead alternates abruptly between the cool and warm phase every 20-30 years. The relationship between the PDO and fire occurrence has been found to vary spatially, and is often investigated along with ENSO activity (Schoennagel et al. 2005, Taylor et al. 2008, Heyerdahl et al. 2001).

### **4.3 Atlantic Multi-Decadal Oscillation**

The Atlantic Multi-Decadal Oscillation (AMO, Figure 2) is described by a low-frequency change in SSTs in the Atlantic Ocean between 0 and 70 °N. The AMO displays strong but low frequency 50-80 year periods (Gray et al. 2004, Schoennagel et al. 2007). McCabe et al. (2004) showed that periods of drought in the southwestern United States correspond with different periods of sea surface temperature anomalies in the North Atlantic basin. In the Southcentral United States, two of the most severe droughts of the 20th century occurred during positive phases of the AMO between 1930 and 1960: the Dust Bowl of the 1930s and the 1950s drought (McCabe et al. 2004). Since 1995, a positive AMO has been observed, mirroring the positive phase of 1930 to 1960 and increasing concerns for severe drought in the southcentral United States. Kitzberger et al. (2007) found that the positive AMO phase synchronized fire activity across the western U.S.

### **4.4 Interactions Between ENSO, PDO, and AMO**

These three climate oscillations (ENSO, PDO and AMO) often have interactions, frequently with one phase intensifying the effects of another during times of synchrony. McCabe et al. (2004) showed that the PDO intensifies the conditions of ENSO. Newman et al. (2003) and Westerling and Swetnam (2003) also displayed that the intensity of the PDO depends on the corresponding phases of ENSO, with an intensifying ENSO influencing PDO in the following winter/spring months. A positive PDO phase (warm SSTs along the western coast of North America) and a negative ENSO (El Niño) phase (warm SSTs in the eastern tropical Pacific) are associated with wetter winters over New

Mexico in both instrumental and reconstructed climate data (Enfield et al. 2001, Stahle et al. 2009). Alternatively, periods of overlapping La Niña and negative PDO produce drier conditions in New Mexico (Stahle et al. 2009).

Evidence exists for climatic oscillations representing a source of variation in fire occurrence in the U.S. Regional trends involving ENSO, PDO, and AMO vary over both timescales and geography. Where teleconnections with regional climate exists, fire occurrence can be influenced through a number of pathways (Westerling et al. 2002, Schoennagel et al. 2005, Taylor et al. 2008). There is a need for the identification and understanding of regional trends in the roles of these patterns, and historical reconstructions of fire history are needed to further assess the impacts of teleconnections at local and regional scales (Bowman 2007).

#### **4.5 Climate-Fire Interactions**

Understanding and investigating climate-fire interactions is vital for evaluating how climate affected fire regimes in the past, and how climate changes are likely to impact fire activity in the future. The synchronous nature of climate phases and their associated influences on fire frequency also needs further consideration in the southcentral U.S. Climate is an influence on wildland fire activity (Guyette et al. 2012), and the frequency of fire in the southcentral U.S. is expected to increase in response to the projected increased temperatures and droughts in the 21st century (Brown 2006, Westerling et al. 2006, Guyette et al. 2014). Further evidence of regional- and broad-scale synchrony or asynchrony between climate and wildfire activity is needed in the southcentral United States to properly address potential concerns of the projected change

in drought. This can be achieved by assessing the relationships between ENSO and PDSI and their influences on fire occurrence (Kitzberger et al. 2007).

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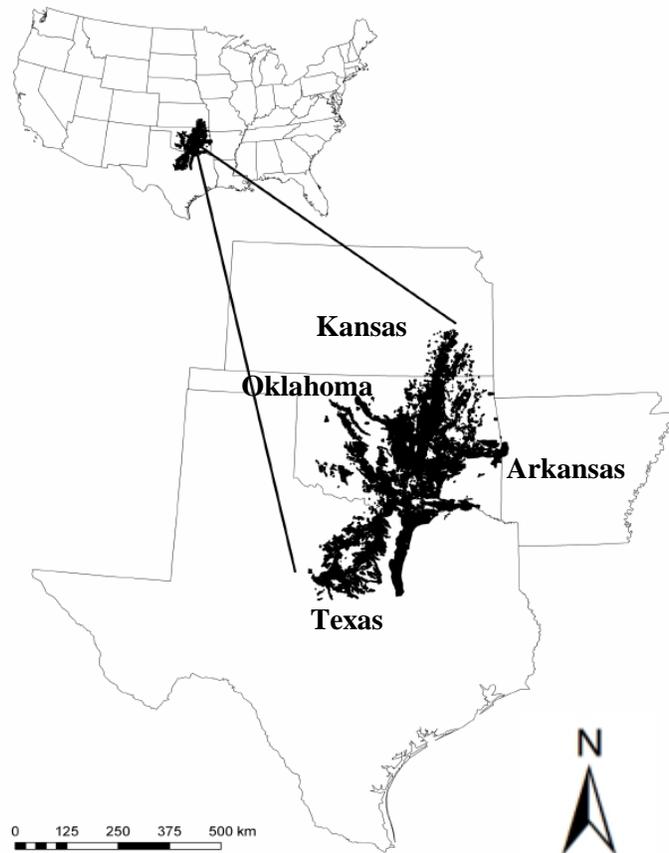
## CHAPTER TWO

### Historical Fire Occurrence at Two Scales in the Cross Timbers of Oklahoma and Texas, United States

#### 1. Introduction

The Cross Timbers ecoregion in the southcentral United States is a patchwork of forest, woodland, savanna, and prairie, dominated by post oak (*Quercus stellata*) and blackjack oak (*Quercus marilandica*) (Figure 3) (Duck and Fletcher 1943; Rice and Penfound 1959; Hoagland et. al. 1999). The region constitutes a broad ecotone between the eastern deciduous forest and the Great Plains prairie ecosystems (Kuchler 1964). The characteristic woody vegetation of the Cross Timbers tends to be found on steep or infertile terrain that limits their growth and, hence, economic value (Therrell and Stahle 1998). These conditions are thus ideal for finding centuries-old oak trees, with potential for dendrochronological studies across large expanses, such as fire histories.

Historically, anthropogenic fire played a role in multiple regions of the United States (Pyne 1982; Frost 1988; Bowman et al. 2009). In the eastern United States, historical fire occurrence over the last three centuries in a region has corresponded to the patterns of human settlement and land use (Guyette et al. 2002, Brose et al. 2015). Humans historically used fire for a variety of reasons including clearing land for grazing of animals, controlling harmful or unwanted pests, warfare, hunting and for communication (Day 1953; Moore 1972; Williams 1989; Pyne 2001; Stewart 2002). Prior to Euro-American settlement (EAS), diseases caused depopulation of Native peoples (Williams 1989). Additionally, Euro-American settlement displaced or relocated many Native American groups, altering the land use at a local, landscape, and sometimes regional level (Williams 1989).

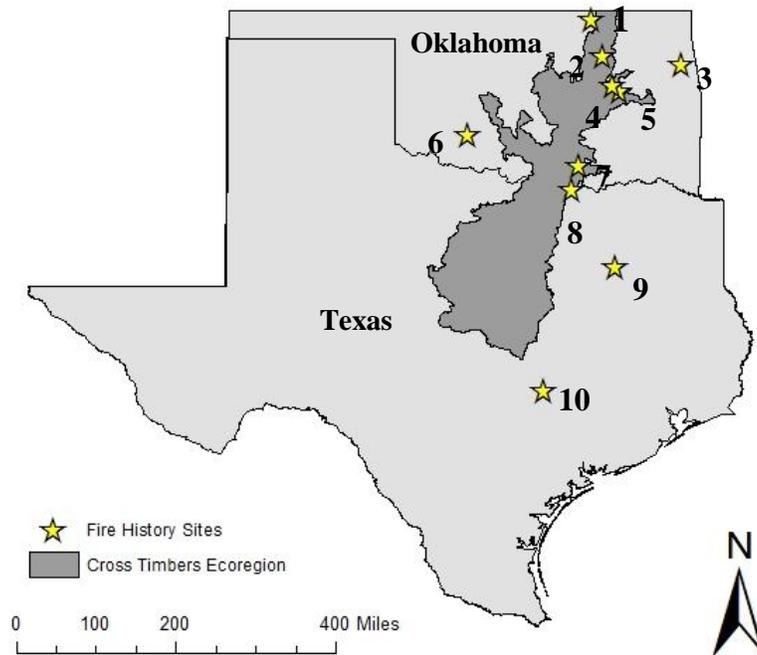


**Figure 3.** Map of the Cross Timbers ecoregion derived from Kuchler (1964).

Fire varies both spatially and temporally due to variations in drivers of fire and their influences (Turner 1987, Yocum 2017). Recent studies show that networks of fire history data can demonstrate how historical fire regimes have been controlled and driven by a variety of factors- including localized vegetation change, shifts in human populations, and climatic conditions (Guyette 2002, Stambaugh et al. 2016, Yocom 2017). Most fire history sites cover relatively small areas ( $\sim 1 \text{ km}^2$ ), making understanding spatial-temporal variability of fire regimes difficult at landscape to regional scales without large datasets or modeling approaches (Swetnam and Baisan 1996, Stambaugh and Guyette 2008, Guyette et al. 2012).

Certain literature suggests that in the Cross Timbers fire frequency has decreased throughout the nineteenth and twentieth centuries (Stambaugh 2011, Stambaugh 2014), while others show evidence of an increase in fire frequency through this time period (Clark et al. 2007, DeSantis 2010, Allen 2011, Stambaugh et al., 2017b). Heterogeneity in both topography and vegetation across the landscape has potential implications on the spatial and temporal variability of historical fire. At the landscape scale, great variability exists in fire frequency (Stambaugh et al. 2016). Understanding the variability of the frequency, severity, seasonality, extent and sources of ignition are of interest to managers of both fire and vegetation across the landscape. Additionally, recent high severity fires in the southcentral U.S. have raised interest in understanding historical fire regime characteristics, particularly the likelihood and effects of high-severity fires.

The goal of this study was to evaluate and explore the extent, frequency, seasonality, and severity of fires across the Cross Timbers, and through time. I reconstructed historical fire events at three new study sites in unrepresented geographic locations. Fire event chronologies were developed from fire scars spanning three centuries. These chronologies were compared with data from ten existing fire sites to evaluate fire regime characteristics and changes at a regional scale. Finally, these findings were discussed in the framework of opportunities and challenges associated with utilizing historical fire regime information in modern conservation and restoration management.



**Figure 4.** Cross Timbers Ecoregion is delineated in dark grey. Fire history sites are shown with labeled yellow stars and represent a common time period of fire occurrence data from 1770-2002. 1: Tallgrass Prairie Preserve 2: Keystone Ancient Forest Preserve 3: Nickel Family Nature and Wildlife Preserve 4: Okmulgee Game Management Area 5: Deep Fork National Wildlife Refuge 6: Wichita National Wildlife Refuge (Cache Creek, Hollis Canyon, French Lake, Rain Gauge Flat) 7: Tishomingo National Wildlife Refuge 8: Hagerman National Wildlife Refuge 9: Purtil Creek State Park 10: Bastrop State Park.

## **2. Methods**

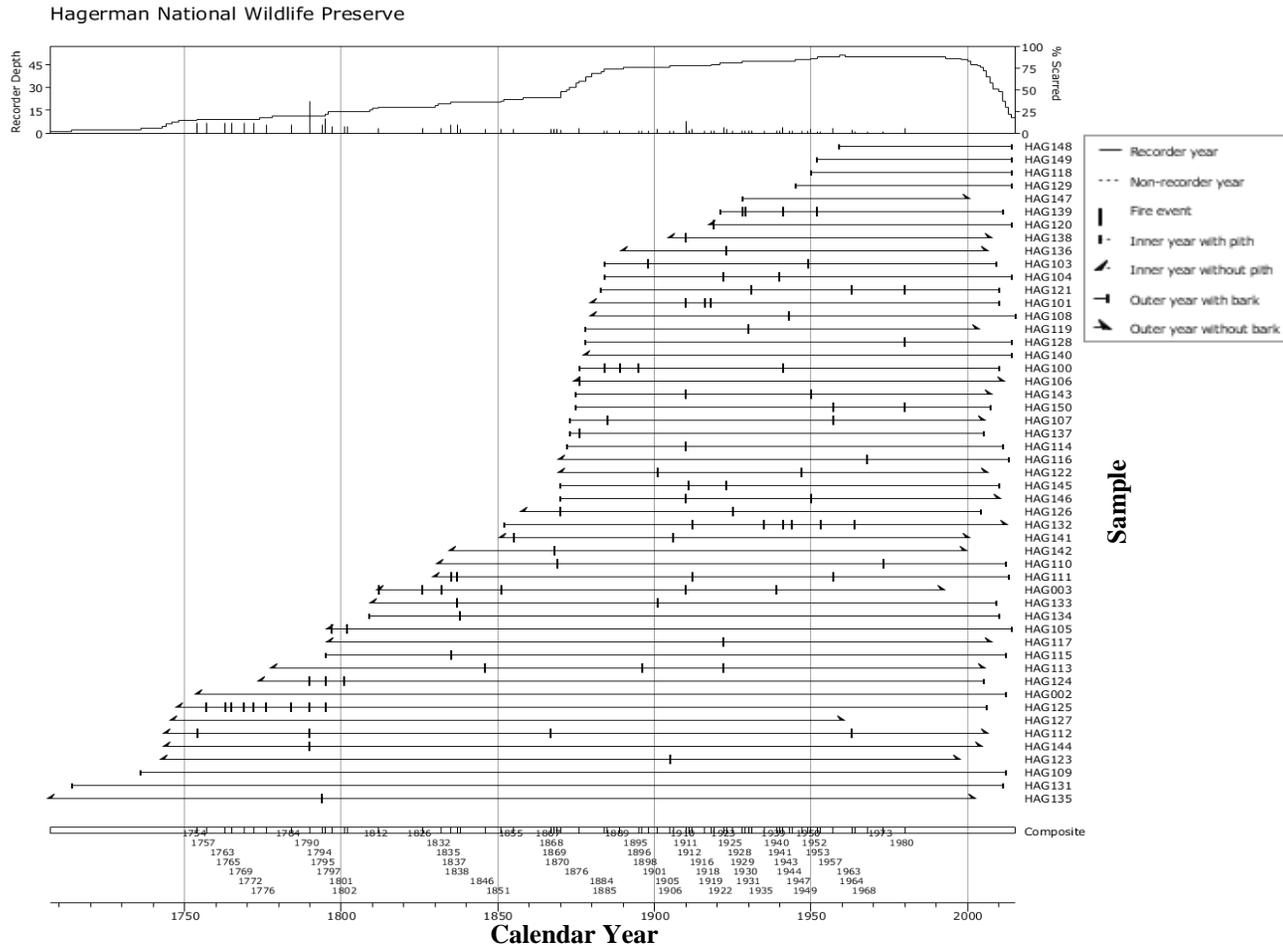
### **2.1. Study Sites**

Three study sites were located in eastern Oklahoma and northern Texas, contained within Region 2 of the U.S Fish and Wildlife Refuge system (Figure 4). Site selection occurred across Region 2, looking for sites with criteria favorable for fire history reconstruction. These criteria included the presence of three centuries of tree-ring data and the presence of scars. Post oak was selected for this study because of its ability to withstand fire, produce scars, but not die following repeated fires. Site selection was done at 1 km<sup>2</sup> areas, which are commonly used for local fire history reconstruction (Stambaugh et al. 2016). A study site of 1 km<sup>2</sup> captures variable topography, adequate sample numbers, and allows for the comparison among other equally-sized sites (Falk and Swetnam 2003, Fulé et al. 2004, Stambaugh 2014).

#### **2.1.1. Hagerman National Wildlife Refuge (NWR)**

Hagerman NWR is located at 33.75546 N, -96.68206 W in Grayson, County, TX and at the intersection of the Blackland Prairies and the Eastern Cross Timbers (Figure 4, Figure 5) (Omerick, 1987; Texas Parks and Wildlife Department, 2002). Hagerman NWR was established in 1946 as a portion of the area surrounding the Big Mineral Arm of Lake Texoma in north-central Texas (U.S. Army Corps of Engineers, 2001; U.S. Fish and Wildlife Service, 1995). The refuge consists of approximately 5000 hectares, providing habitat for wildlife (U.S. Fish and Wildlife Service, 1995). Mean annual temperature (1974-2011) at the refuge is 20°C and the 55 year rainfall average is 100.69 cm (Texas Annual Climatological Summary, 2011).

A total of fifty trees were sampled at Hagerman NWR, taken from the northwest portion of the refuge south of Lake Texoma near the Sandy Creek Picnic Area, located at the southern border road. Topography on the refuge is slightly to steeply sloping, and soils vary from heavy clays on the southern and eastern portion of the refuge to light sandy soils on the northern and western portion (Spearing 1991). Post oak and blackjack oak are found in sandy soil on the refuge. Black hickory (*Carya texana*), Eastern red cedar (*Juniperus virginiana*), and winged elm (*Ulmus alata*) are important subordinate species. Invasive Chinaberry (*Melia azedarach*) is present throughout the northwestern portion of the refuge.

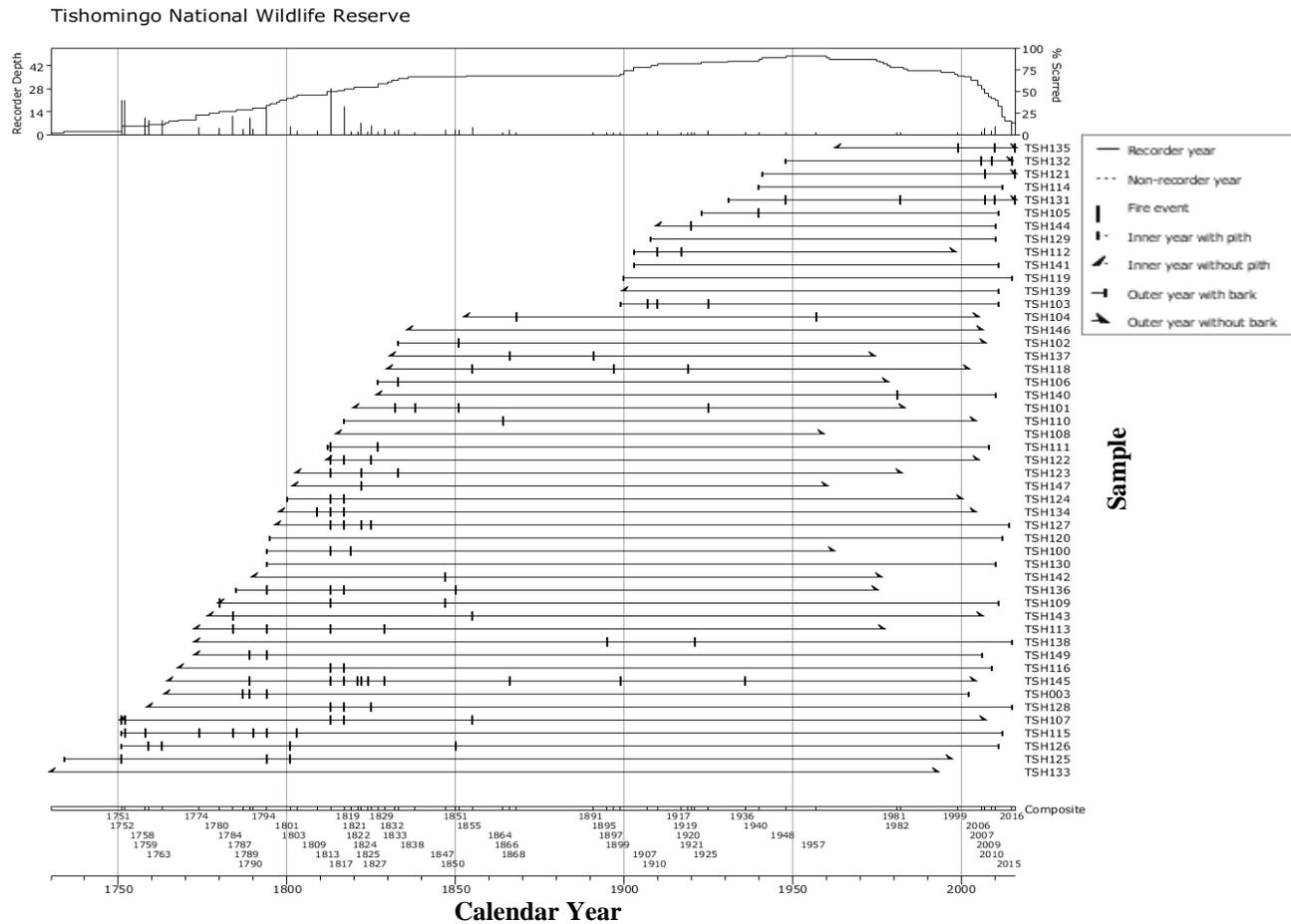


**Figure 5.** Hagerman National Wildlife Refuge, TX fire history chart. Horizontal lines represent the periods of tree-ring records for individual trees (sample numbers appear on far right side). On the left end of lines, vertical lines indicate pith years while diagonal lines indicate inner ring year (rings missing to center). On the right ends of lines, vertical lines indicate bark years while diagonal lines indicate outer ring years (rings missing to bark). Fire scar dates are shown at bottom of chart with labeled dates. The top graph shows a line graph of the number of samples recording fire in the site, and a bar graph of the percentage of trees scarred in a fire event.

### **2.1.2. Tishomingo National Wildlife Refuge (NWR)**

Tishomingo NWR is located at 34.18097 N, -96.66113 W in Johnston and Marshall Counties in south central Oklahoma, and was established in 1946 to benefit migratory waterfowl in the Central Flyway (Figure 4, Figure 6). Eight kilometers southeast of the refuge, Fort Washita exists as a National Historic Landmark of the military post that was established in 1842 to protect the Choctaw and Chickasaw Nations from the Plains Indians during resettlement efforts (National Register Properties in Oklahoma, 2017). The fort was abandoned by federal forces at the start of the Civil War, and never reoccupied by the United States Army. Mean annual temperature (1974-2011) at Tishomingo NWR is 17°C with a mean annual precipitation of 106 cm but is highly variable with a range of 42 to 176 cm (Oklahoma Climatological Survey 2010).

Fifty trees were sampled from the southern part of the refuge, south of the section of Lake Texoma contained in the refuge borders near Rock Creek. Parent materials are primarily sandstone and shale; and soil types are stony and gravelly fine sandy loam and very cobbly clay (Soil Survey Staff 2009). Post oak and Blackjack Oak are dominant on the site, and persist along with prairie openings that include Little Bluestem (*Schizachyrium scoparium*) and Big Bluestem (*Andropogon gerardi*).

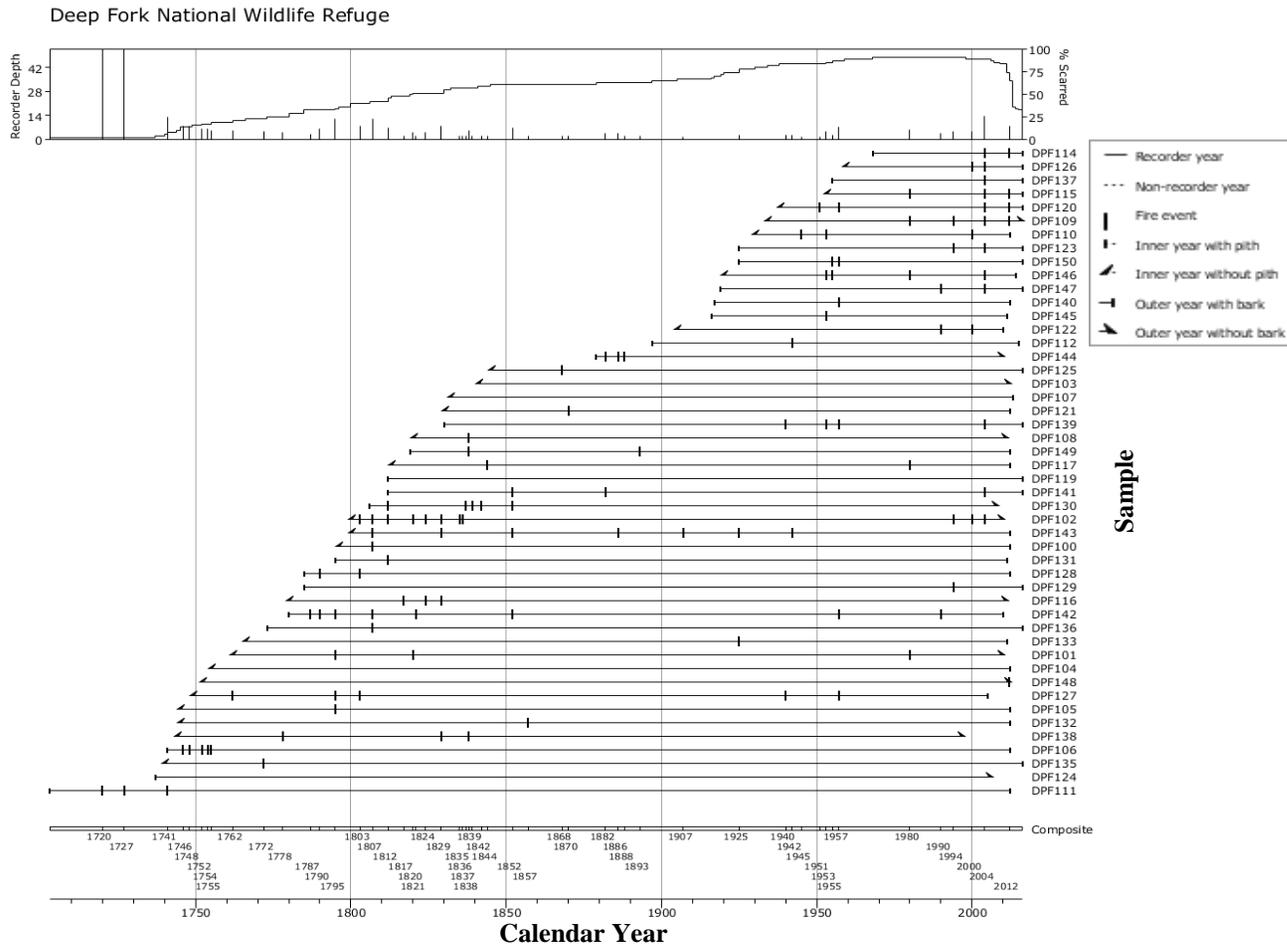


**Figure 6.** Tishomingo National Wildlife Refuge, TX fire history chart. Horizontal lines represent the periods of tree-ring records for individual trees (sample numbers appear on far right side). On the left end of lines, vertical lines indicate pith years while diagonal lines indicate inner ring year (rings missing to center). On the right ends of lines, vertical lines indicate bark years while diagonal lines indicate outer ring years (rings missing to bark). Fire scar dates are shown at bottom of chart with labeled dates. The top graph shows a line graph of the number of samples recording fire in the site, and a bar graph of the percentage of trees scarred in a fire event.

### 2.1.3. Deep Fork National Wildlife Refuge (NWR)

Deep Fork NWR is located at 35.53833 N, -95.92761 W in Okmulgee County, in eastern Oklahoma (Figure 4, Figure 7). The refuge encompasses 4000 hectares with a management emphasis of providing protected habitat to neo-tropical migrating songbirds. Upland parent materials are primarily sandstone and shale; and soil types are stony and gravelly fine sandy loam and silty clay (Soil Survey Staff 2009). Most of the forested land of the refuge is young (<120 years) although patches of mature forest can be found. Mean annual temperature (1974-2011) is 15°C and the mean annual precipitation is 110 cm. Annual precipitation can be highly variable with a range of 55 to 156 cm (Oklahoma Climatological Survey 2010).

Fifty trees were sampled from the southern part of the refuge. Primary species at the study site include both post oak and blackjack oak, while annual flood events support a bottomland hardwood forest consisting of bur oak (*Quercus macrocarpa*), pin oak (*Quercus palustris*), black walnut (*Juglens nigra*), pecan (*Carya illinoensis*), hackberry (*Celtis occidentalis*), and river birch (*Betula nigra*).



**Figure 7.** Deep Fork National Wildlife Refuge, OK fire history chart. Horizontal lines represent the periods of tree-ring records for individual trees (sample numbers appear on far right side). On the left end of lines, vertical lines indicate pith years while diagonal lines indicate inner ring year (rings missing to center). On the right ends of lines, vertical lines indicate bark years while diagonal lines indicate outer ring years (rings missing to bark). Fire scar dates are shown at bottom of chart with labeled dates. The top graph shows a line graph of the number of samples recording fire in the site, and a bar graph of the percentage of trees scarred in a fire event.

#### 2.1.4. Existing Fire History Data

Ten additional sites in the greater Cross Timbers region were incorporated into the data analysis for this study (Figure 4). These additional sites allowed for the evaluation of the significance of new findings, and expanded our understanding of fire occurrence from the site to the regional level. Existing fire history data were provided by authors with publications drawn from similar study areas and using the same sampling methods. The locations of these sites are shown in Figure 4, which details the Cross Timbers ecoregion and vicinity. Bastrop State Park (BSP) is located in southcentral Texas, and much of the park is mixed pine and oak forest (Table 1). At BSP, fire has significantly decreased since the 1920s (Stambaugh et al., 2017b). The Wichita Mountains Wildlife Refuge (WMWR) includes four of the sampled sites each separated by up to 6 km within the refuge (Cache Creek, French Lake, Hollis Canyon and Rain Gauge Flat, Table 1) over a matrix of oak forests, woodlands, and openings. A decrease in fire occurrence in the early twentieth century was observed at all sites on the refuge (Stambaugh et al., 2014). The Nature Conservancy's Keystone Ancient Forest Preserve (KAFF) lies in the northern Cross Timbers ecoregion in southern Osage County, and is characterized as old-growth due to the presence of post oak and eastern red cedar trees greater than 300 and 500 years old, respectively (Table 1, Therrel and Stahle 1998). The frequency of fire at the KAFP increased following the establishment of Oklahoma's statehood and European-American settlement in the area (Clark 2007). The Nickel Family Nature and Wildlife Preserve is managed by the Nature Conservancy, and living and remnant shortleaf pines (*Pinus echinata*) occur readily on the site (Table 1). After the immigrations of native peoples into northeastern Oklahoma 1791-1880, fire

frequency at the site increased, and then decreased after 1925 due to fire suppression until recent prescribed burning by the Nature Conservancy (Stambaugh et al. 2013). The Okmulgee Game Management Area (OGMA) is administered by the Oklahoma Department of Wildlife Conservation (ODWC) and is composed of primarily upland post oak and blackjack oak (Table 1). The OGMA has seen an increase in fire from the eighteenth to the early twenty-first century (DeSantis et al. 2010). Purtil Creek State Park is located in northern Texas, at the grassland-woodland transition zone at the southern periphery of the tallgrass prairie ecosystem (Table 1). Purtil Creek observed an overall trend of decreasing fire occurrence through time, and a fifty-year period without fire in the late nineteenth century (Stambaugh et al., 2011). The Nature Conservancy's Tallgrass Prairie Preserve represents the largest protected area of tallgrass prairie in North America (The Nature Conservancy, Table 1). The MFI shortened between the pre-EAS and post-EAS period, and no extended periods without fire were recorded in the study area (Allen and Palmer 2011).

**Table 1.** Fire history study site summary information for the greater Cross Timbers region.

<b>Site Name</b>	<b>Date Range</b>	<b>Number of Trees</b>	<b>Latitude/ Longitude</b>	<b>Species</b>
Bastrop State Park	1653-2011	50	30.11017 N, - 97.2869 W	Post Oak
Cache Creek	1636-2010	43	34.75096 N, - 98.68206 W	Post Oak
Deep Fork NWR	1703-2015	48	35.53833 N, - 95.92761W	Post Oak
French Lake	1700-2005	54	34.75096 N, - 98.68206 W	Post Oak
Hagerman NWR	1701-2015	51	33.75546 N, - 96.78152 W	Post Oak
Hollis Canyon	1720-2010	46	34.75096 N, - 98.68206 W	Post Oak
Keystone Ancient Forest Preserve	1770-2002	51	36.18111 N, - 96.22975 W	Post Oak, Blackjack Oak, Shumard Oak, Black Hickory
Nickel Family Nature Center Okmulgee	1639-2005	34	36.03435 N, - 94.80823 W	Shortleaf Pine
Game Management Area	1690-2008	69	35.64454 N, - 96.04499 W	Post Oak
Purtis Creek State Park	1681-2005	49	32.35367 N, - 95.99358 W	Post Oak
Rain Gauge Flat	1746-2009	46	34.75096 N, - 98.68206 W	Post Oak
Tallgrass Prairie Preserve	1729-2005	54	36.84614 N, - 96.42290 W	Post Oak
Tishomingo NWR	1730-2015	49	34.18097 N, - 96.66113 W	Post Oak
<b>All Sites (Max)</b>	<b>1636-2015</b>	<b>596</b>		
<b>All Sites (Common)</b>	<b>1770-2002</b>	<b>573</b>		

**Table 2.** Summary statistics of fire scar history data stratified by study site across the greater Cross Timbers region.

<b>All Years</b>	<b>Bastrop</b>	<b>Cache Creek</b>	<b>* Deep Fork</b>	<b>French Lake</b>	<b>* Hagerman</b>	<b>Hollis</b>	<b>Key-stone</b>	<b>Nickel</b>	<b>Okmulgee</b>	<b>Purtis</b>	<b>Rain Gauge Flat</b>	<b>Tall-grass Prairie</b>	<b>* Tishomingo</b>	<b>All Sites</b>
<b>Time Period</b>	1653-2011	1637-2009	1703-2016	1712-2005	1707-2015	1720-2009	1770-2002	1646-2005	1742-2008	1691-2005	1746-2008	1729-2005	1730-2016	1637-2016
<b>No. Trees</b>	50	46	48	54	51	46	51	34	69	49	43	54	49	644
<b>No. Fire Intervals</b>	45	34	49	59	66	34	76	101	95	29	34	111	57	60.77
<b>Mean Fire Interval</b>	5.93	7.94	5.53	7.82	3.42	7.09	2.86	3.4	2.59	8.07	4.73	2.03	4.65	5.08
<b>Fire Interval Range</b>	1-36	1-66	1-23	1-19	1-14	1-27	1-15	1-30	1-24	2-50	1-26	1-16	1-24	1-28
<b>Weibull Median</b>	3.96	4.5	4.56	3.77	2.87	6.14	2.35	2.63	1.98	6.56	5.53	1.59	4.68	3.93
<b>Mean % Trees Scar</b>	7%	12%	13%	6%	6%	10%	10%	5%	3%	11%	12%	6%	11%	9%
<b>Range % Trees Scar</b>	2-25%	3-50%	2-33%	2-36%	2-44%	2-29%	3-33%	100% 1-	1-12%	2-37%	2-60%	2-30%	2-56%	2-40%
<b># Fire Scars</b>	98	91	115	122	92	105	138	205	172	83	102	242	112	129
<b>% Dormant Fires</b>	58%	97%	89%	78%	71%	88%	68%	90%	60%	93%	80%	69%	87%	79%
<b>% Growing Fires</b>	21%	2%	3%	2%	4%	0%	20%	4%	3%	0%	6%	20%	3%	7%
<b>% Undetermined</b>	20%	1%	9%	20%	25%	12%	12%	6%	36%	7%	14%	11%	11%	14%
<b>Spatial Extent (km<sup>2</sup>)</b>	1	1	1	1	1	1	0.4	1.2	1	0.5	1	1.6	1	140.00 0

\*New study sites

**Table 3.** Summary statistics of fire scar history data stratified by study site across the greater Cross Timbers region during the Pre-European American Settlement period.

<b>Pre-European American Settlement</b>	<b>Bastrop</b>	<b>Cache Creek</b>	<b>* Deep Fork</b>	<b>French Lake</b>	<b>* Hagerman</b>	<b>Hollis</b>	<b>Key-stone</b>	<b>Nickel</b>	<b>Okmulgee</b>	<b>Purtis</b>	<b>Rain Gauge Flat</b>	<b>Tall-grass Prairie</b>	<b>* Tishomingo</b>	<b>All Sites</b>
<b>Time Period</b>	1653-1829	1637-1899	1704-1899	1712-1899	1707-1842	1720-1899	1772-1907	1650-1889	1750-1899	1690-1820	1746-1899	1770-1871	1736-1842	1650-1907
<b>No. Trees</b>	30	35	34	52	20	33	51	29	62	28	38	54	35	501
<b>No. Fire Intervals</b>	10	29	34	40	19	23	29	79	33	18	27	20	26	29.77
<b>Mean Fire Interval</b>	10.9	6.45	4.47	4.4	4.42	6.91	4.14	2.95	4.3	6.67	4.96	3.5	3.35	5.19
<b>Fire Interval Range</b>	2-27	1-53	1-12	1-19	1-14	1-25	1-15	1-17	1-24	2-14	1-17	1-16	1-11	1-53
<b>Weibull Median</b>	8.41	4.25	3.95	3.56	3.82	5.19	3.33	2.51	3.23	6.37	4.16	3.65	2.95	4.26
<b>Mean % Trees Scar</b>	11%	12%	9%	8%	13%	15%	15%	13%	3%	16%	13%	11%	16%	12%
<b>Range % Trees Scar</b>	3-25%	3-50%	3-33%	2-50%	6-44%	3-50%	7-33%	3-50%	2-11%	4-37%	3-60%	5-20%	3-56%	7-60%
<b># Fire Scars</b>	19	71	81	87	33	55	41	173	40	50	79	24	67	820
<b>% Dormant Fires</b>	58%	97%	73%	76%	42%	87%	71%	91%	70%	88%	80%	50%	82%	74%
<b>% Growing Fires</b>	16%	1%	5%	2%	6%	0%	15%	3%	5%	0%	5%	8%	3%	5%
<b>% Undetermined</b>	26%	1%	22%	22%	52%	13%	15%	6%	25%	12%	15%	42%	15%	20%

\* New study sites

**Table 4.** Summary statistics of fire scar history data stratified by study site across the greater Cross Timbers region during the Post-European American Settlement period.

<b>Post-European American Settlement</b>	<b>Bastrop</b>	<b>Cache Creek</b>	<b>* Deep Fork</b>	<b>French Lake</b>	<b>* Hagerman</b>	<b>Hollis</b>	<b>Key-stone</b>	<b>Nickel</b>	<b>Okmulgee</b>	<b>Purtis</b>	<b>Rain Gauge Flat</b>	<b>Tall-grass Prairie</b>	<b>* Tishomingo</b>	<b>All Sites</b>
<b>Time Period</b>	1830-1940	1901-2010	1900-2016	1901-2005	1842-1946	1901-2010	1908-2001	1890-1925	1900-1988	1820-1924	1901-2009	1871-1914	1842-1946	1830-2016
<b>No. Trees</b>	50	43	48	54	48	46	51	12		47	46	54	47	546
<b>No. Fire Intervals</b>	32	4	14	18	35	9	46	16	52	10	6	19	19	21.54
<b>Mean Fire Interval</b>	3.38	19.25	7.5	5.22	2.8	10.67	2	2.12	1.67	9.8	16.67	2.16	4.89	6.78
<b>Fire Interval Range</b>	1-11	2-66	2-23	1-19	1-12	1-27	1-6	1-4	1-5	2-50	7-26	1-5	1-23	1-66
<b>Weibull Median</b>	2.8	8.71	6.04	4.04	2.31	8.85	1.86	2.02	1.54	6.78	16.33	2.18	3.75	5.17
<b>Mean % Trees Scar</b>	5%	11%	9%	4%	4%	11%	8%	19%	3%	9%	9%	4%	4%	8%
<b>Range % Trees Scar</b>	2-11%	3-17%	2-26%	2-10%	2-14%	2-29%	3-29%	9-63%	1-12%	2-21%	3-23%	4-13%	2-9%	1-63%
<b># Fire Scars</b>	75	20	81	35	49	48	97	24	132	33	23	23	63	703
<b>% Dormant Fires</b>	57%	95%	89%	83%	76%	88%	67%	88%	58%	100%	83%	65%	87%	80%
<b>% Growing Fires</b>	25%	5%	0%	3%	2%	0%	23%	13%	2%	0%	9%	4%	3%	7%
<b>% Undetermined</b>	20%	0%	11%	14%	22%	13%	10%	0%	39%	0%	9%	30%	10%	14%

\*New study sites

**Table 5.** Summary statistics of fire scar history data stratified by study site across the greater Cross Timbers region during the Recent Use period.

<b>Recent Use</b>	<b>Bastrop</b>	<b>Cache Creek</b>	<b>Deep Fork</b>	<b>French Lake</b>	<b>Hagerman</b>	<b>Hollis</b>	<b>Key stone</b>	<b>Nickel</b>	<b>Okmulgee</b>	<b>Purtis</b>	<b>Rain Gauge Flat</b>	<b>Tall grass Prairie</b>	<b>Tishomingo</b>	<b>All Sites</b>
<b>Time Period</b>	1941-2011	n/a	n/a	n/a	1946-2015	n/a	n/a	1925-1992	1989-2005	n/a	n/a	1915-1989	1946-2015	1915-2015
<b>No. Trees</b>	49	n/a	n/a	n/a	50	n/a	n/a	4	66	n/a	n/a	54	48	271
<b>No. Fire Intervals</b>	1	n/a	n/a	n/a	10	n/a	n/a	4	8	n/a	n/a	59	9	15.17
<b>Mean Fire Interval</b>	n/a	n/a	n/a	n/a	3.3	n/a	n/a	16.75	1.75	n/a	n/a	1.25	7.44	5.08
<b>Fire Interval Range</b>	n/a	n/a	n/a	n/a	1-7	n/a	n/a	8-30	1-2	n/a	n/a	1-5	1-24	1-30
<b>Weibull Median</b>	n/a	n/a	n/a	n/a	2.95	n/a	n/a	16.14	1.79	n/a	n/a	1.17	4.88	5.386
<b>Mean % Trees Scar</b>	4%	n/a	n/a	n/a	3%	n/a	n/a	58%	4%	n/a	n/a	6%	7%	16%
<b>Range % Trees Scar</b>	2-6%	n/a	n/a	n/a	2-6%	n/a	n/a	25-60%	2-9%	n/a	n/a	2-30%	2-25%	2-60%
<b># Fire Scars</b>	4	n/a	n/a	n/a	17	n/a	n/a	7	25	n/a	n/a	194	17	264
<b>% Dormant Fires</b>	75%	n/a	n/a	n/a	82%	n/a	n/a	86%	68%	n/a	n/a	72%	100%	80%
<b>% Growing Fires</b>	25%	n/a	n/a	n/a	6%	n/a	n/a	0%	0%	n/a	n/a	23%	0%	9%
<b>% Undetermined</b>	0%	n/a	n/a	n/a	12%	n/a	n/a	14%	32%	n/a	n/a	5%	0%	11%

\* New study sites

## **2.2. Fire History Reconstruction**

Measures were taken to ensure that data collection remained uniform at all sites, so that data could be better compared. As much as possible, methods described here are comparable to methods in other publications, but these publications should be referenced to understand methods by other researchers. At Wichita National Wildlife Refuge, four sites (Cache Creek, French Lake, Hollis Canyon and Rain Gauge Flat; Stambaugh 2014) were sampled, while at Nickel Family Nature and Wildlife Preserve shortleaf pine was utilized in the reconstruction of the site's fire history (Stambaugh 2013). At the KAFP, fire history reconstruction utilized fire scars from the four most abundant tree species at the site: post oak, blackjack oak, black hickory, and shumard oak (Clark 2007). At each of the three new sites (Hagerman NWR, Tishomingo NWR, Deep Fork NWR), 50 post oak cross-sections were collected during 2015 and 2016.

Samples were taken as cross-sections from the base of trees to capture the greatest possible number of fire scars contained. In some instances, multiple samples were taken from a single tree because additional scars were detected either above or below the original cross-section. Samples were identified based on external characteristics of the tree considering both age and presence of scars. A hammer was used to sound standing and naturally downed trees, and trees were rejected for sampling if significant decay was suspected. An effort was made to minimize fire scar sampling bias due to either tree age or size by sampling small to large diameter and young to old trees (Guyette and Stambaugh, 2004). Locations of samples were recorded using a Global Positioning

System (GPS) unit, and measurements were taken of each sample's physical orientation with respect to aspect, slope and height above ground level.

In the laboratory, cross-sections were surfaced using an electric planer, and the cellular detail of annual rings and fire scar injuries was revealed by sanding with progressively finer sandpaper from ANSI 80 to 1200 grit. Two radii (outer tree-ring to pith) of cross-sections with the least ring-width variability and distortion were chosen for measurement. All tree rings were measured to 0.01 mm precision using a Velmex T.A. measurement station paired with MeasureJ2X software. Cross-dating of samples was done by visual pattern matching of ring-width plots and anatomical ring-width features (Stokes and Smiley, 1968). When cross dating samples from Hagerman NWR, the tree ring-width chronology from Wichita NWR was utilized (Stambaugh 2014). Likewise, dating at Deep Fork NWR utilized the tree ring-width chronology from Okmulgee GMA (DeSantis 2010). Tishomingo NWR and Hagerman NWR are close in proximity, and the Hagerman NWR tree ring-width chronology was utilized in developing a complete chronology at Tishomingo NWR. Innermost and outermost ring dates were recorded for each sample, along with the presence of pith or bark, respectively. COFECHA software (Holmes 1983; Grissino-Mayer 2001) was used to assess inter-tree crossdating. ARSTAN software (Cook and Kairiukstis 1990) was used to develop master chronologies. ARSTAN generates site-level chronologies from tree-ring measurements by detrending and standardizing individual tree-ring series- and then applying a robust estimation of the mean value function to remove effects of endogenous stand disturbances.

Fire scars on lower and upper sample surfaces were identified based on the presence of charcoal, barrier zones, callus tissue and cambial injury (Smith and Sutherland 2001; Stambaugh et al. 2017) and assigned to the first year of growth response evident in the wound wood. Seasonality of fire scars was determined based on the position of the scar within the ring and classified as dormant, earlywood, latewood, or undetermined (Kaye and Swetnam 1999). The time period of each sample and all fire scar years and their seasonality were entered into the FHAES program (Brewer 2017) to plot fire scar chronologies and perform analyses of fire events by event characteristics (i.e. frequency, extent, severity, seasonality) and by time periods.

### **2.3. Data Analysis**

Fire frequencies increase with the size of the area under consideration and fire history data create statistics that are spatially specific (Falk et al., 2007, Stambaugh et al., 2016). In consideration of this, fire event summary statistics were reported at two scales: (a) at individual study sites (~1km<sup>2</sup>) and (b) at the region (all study sites combined, ~140,000 km<sup>2</sup>). At both scales, fire event data were summarized for the entire periods of record (Table 2) and for three different sub-periods corresponding to: pre-European American Settlement (pre-EAS, Table 3), post-European-American Settlement (post-EAS, Table 4), and Recent Use (Table 5). Sub-periods were chosen based on regional documented changes in land uses. For each study site, these periods differed by year and time period breakdowns were maintained from original publications (Table 2-5).

At Bastrop State Park, the pre-EAS period (1653-1829) spanned the beginning of the tree-ring record to the beginning of the Alum Creek community in the area (Bastrop

Historical Society, Stambaugh et al. 2017b). The post-EAS time period (1830-1940) covered both EAS and regional development (Stambaugh et al. 2017b). Finally, the public ownership period at Bastrop State park covered the fire suppression period until the catastrophic fire that killed the trees in the sample area (1940-2011, Stambaugh et al. 2017b). At all four sites at Wichita NWR (Cache Creek, French Lake, Hollis Canyon and Rain Gauge Flat), time-period breakdowns were done in two parts. The Pre-EAS period (Cache Creek: 1637-1900; French Lake: 1712-1900; Hollis Canyon: 1720-1900; Rain Gauge Flat: 1746-1900, Table 3) encompasses the establishment of Fort Sill (Wittry 1961) and an increase in human occupation in the area (Stambaugh 2014). The post-EAS period (Cache Creek: 1901-2010; French Lake: 1901-2005; Hollis Canyon: 1901-2010; Rain Gauge Flat: 1901-2009) corresponded to a transition to public ownership for the refuge land area (USFWS 2005, Stambaugh 2014, Table 4). The KAFP pre-EAS period (1772-1907, Table 3) represented the beginning of the fire scar record to Oklahoma Statehood (Clark 2007). Prior to 1907, Osage County was occupied by Osage and Cherokee Native Americans. The post-EAS period (1908-2001, Table 4) represented the period following Oklahoma's statehood. At the Nickel Family Nature and Wildlife Preserve, the pre-EAS period corresponded to Native American settlement and migration (1650-1889, Table 3), the post-EAS period from (1890-1925, Table 4), and a fire suppression period during recent use (1925-1992, Table 5, Stambaugh et al. 2013). At Okmulgee GMA, time periods were maintained from the original publication with a pre-EAS period of 1750-1899 (Table 3) and a post-EAS period of 1900-1988 (Table 4, DeSantis 2010). The recent use period of 1989-2005 (Table 5) corresponded to a period of prescribed burning at the GMA (DeSantis 2010). At Purvis Creek State Park, the pre-

EAS period (1690-1820, Table 3) corresponded to a time period without European-American influence and the post-EAS period spanned 1820-1924 (Table 4). After 1924, there was an extended period (1924 to 2005) without fire (Stambaugh et al. 2011). At Tallgrass Prairie Preserve, the Pre-EAS period spanned 1770-1871 (Table 3), while the post-EAS period covered 1871-1914 (Allen and Palmer 2011, Table 4). A third period was analyzed here, coinciding with a ranching period from 1915-1989 (Allen and Palmer 2011, Table 5).

For the new fire history sites (Hagerman NWR, Tishomingo NWR, Deep Fork NWR), time periods were analyzed corresponding to the dominant culture or land use, stratified across three time periods (Table 3-5), and for all years in record (Table 2). At Deep Fork NWR, fire scar data were analyzed in a pre-EAS period from 1704-1899. This time period was chosen because although Native American populations in the area had fluctuated with both Osage and Creek settlements following the Indian Removal Act of 1830 (Bailey 1973), the period following 1900 observed a development of further EAS influence via the incorporation of nearby Okmulgee, and the establishment of Oklahoma's statehood (Okmulgee Historical Society 1985). The post-EAS period was considered to be from 1900-2016. At both Hagerman NWR and Tishomingo NWR, the same periods of analysis were used as the sites are in close proximity (60 km). Fort Washita was established in 1842 just 8 km from Tishomingo NWR, and 40 km from Hagerman NWR by the U.S. Government to protect the Choctaw and Chickasaw Nations from the Plains Indians during resettlement efforts (National Register Properties in Oklahoma, 2017). For Hagerman NWR, the pre-EAS period was 1707-1842, while this period spans 1736-1842 at Tishomingo NWR (Table 3). The post-EAS period at both

refuges was from 1842-1946 (Table 4) and the recent use period spanned 1946-2015 for both refuges (Table 5).

Summary statistics were generated for fire extent, fire frequency, fire severity, and fire seasonality. A fire extent index (FEI) (Guyette et al. 2002, Muzika et al. 2015) was used to evaluate the extent of fire occurrence across all sites. In this analysis, I first calculated individual site averages of percent trees scarred at each site. From there, I determined how many sites were scarred for all calendar years in the record (0-13). Finally, I calculated the average percent of trees scarred in all calendar years, using only those sites recording fire in that year. Using these data, the FEI was calculated from the number of sites scarred in a year (0 to 13, a value reflecting regional spatial extent of fire in a year) and percent of trees scarred in that year (range= 0-100, a value reflecting the scale of fire severity). The FEI is the product of the number of sites scarred and the percent of trees scarred at all the sites (Equation 1).

$$\text{FEI for year } x = (\# \text{ fire scarred sites}) (\% \text{ trees fire scarred}) \quad (1)$$

To assess fire frequency, Kolmogorov-Smirnov (K-S) goodness-of-fit tests were used to determine whether a Weibull distribution described the fire interval data better than a normal distribution. Mean fire intervals (MFIs) were derived from the composite fire scar chronology and represented the occurrence of fire somewhere in the study area. Both the Weibull Median Interval (WMI) and the MFI were used to determine central tendency in the distribution of fire interval data. The WMI gives a more flexible frequency distribution and more adequately captures skewed data than the MFI.

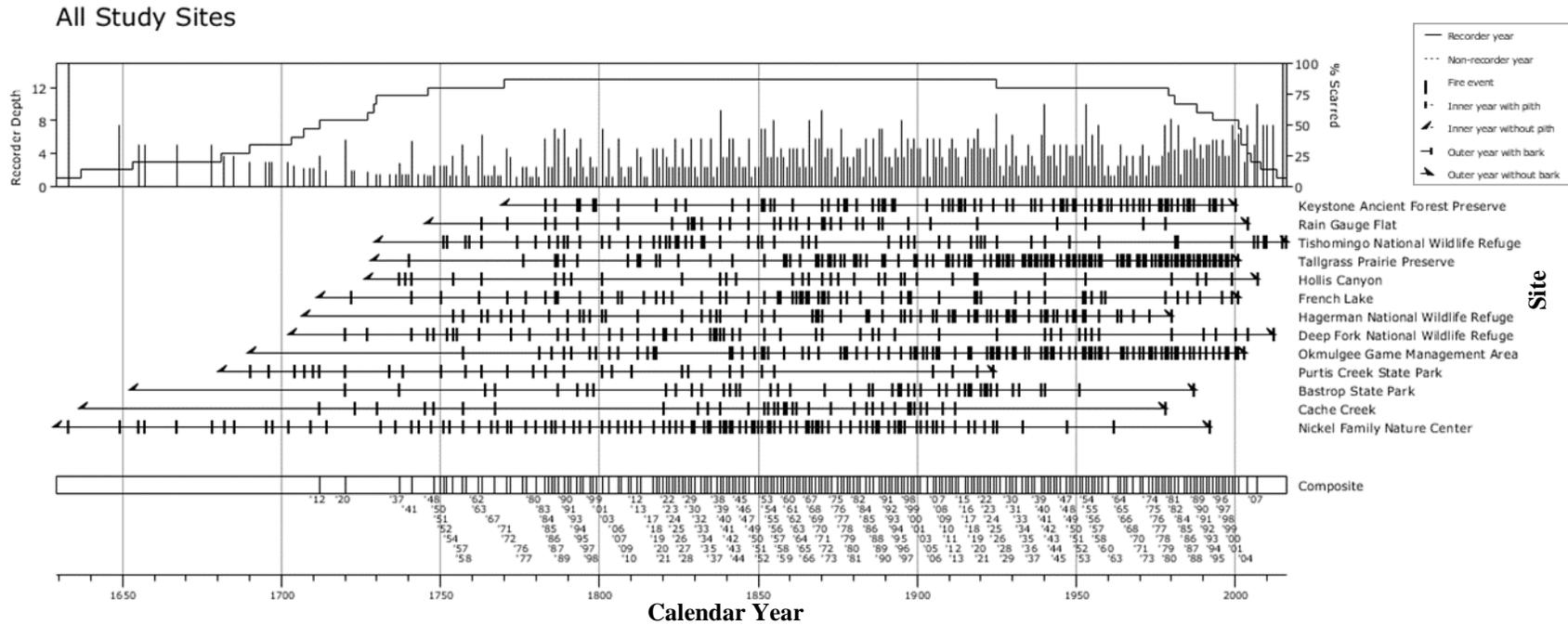
Fire severity was calculated as the percentage of trees scarred in fire events where sample depth was at least three trees. In this analysis, increasing percentages of trees scarred during fire events was assumed to represent increasing fire severity. This assumption holds true in the absence of stand-replacing fires, for which there was no evidence for in sampling. At each site, the availability of 300+ year old post oaks indicates that no stand-replacing events occurred in the last three centuries at these sites, while stand-replacing events may have occurred elsewhere. The exception to this is at Bastrop State Park, where, in 2011, a stand-replacing event killed the samples used in this analysis. For this reason, no data is available at Bastrop State Park following 2011, when the collection of fire scar samples was completed (Stambaugh et al. 2017b). Long-term trends in fire severity were evaluated by plotting the average percentages of trees scarred by using a moving decadal window.

Fire seasonality was assessed and assigned for a majority of samples by evaluating the scar position within each annual growth ring (Dieterich and Swetnam 1984, Guyette et al. 2002). However, some scars' seasonality was undetermined (U) due to distortion or decay at the fire scar location within the sample. The season of fire was classified as earlywood (E), latewood (A), dormant (D), or undetermined (U). Growing-season fires (earlywood and latewood fire events) were fire scar events that occurred between approximately March and July, while dormant-season events occurred approximately between July and March (Stahle 1990, Guyette and Sambaugh 2004).

### **3. Results**

#### **3.1 Site-scale Fire Histories (~1 km<sup>2</sup>)**

Of new fire-history collections, 148 trees were sampled across three sites. With the addition of existing regional fire history data, a total of 596 trees were utilized across thirteen study sites (Table 1, Figure 8). The maximum time period spanned by any site was 1636-2010 (374 years, Cache Creek, Table 1). A common period of 1770-2002 (232 years) was shared across all thirteen sites. In this common period, there were 223 fire events recorded (222 fire intervals). The average number of fire intervals per site was 61. The length of fire intervals ranged from 1 to 66 years, with the smallest range observed at Hagerman NWR (1-14 years), and the largest range observed at Cache Creek (1-66 years, Table 2). The average MFI for all sites was 5.08 years, calculated as an average of the MFIs across all thirteen sites (Table 2). The shortest MFI for any site was Tallgrass Prairie Preserve (2.03 years), while the longest MFI was observed at Purtil Creek State Park (8.07 years, Table 2).



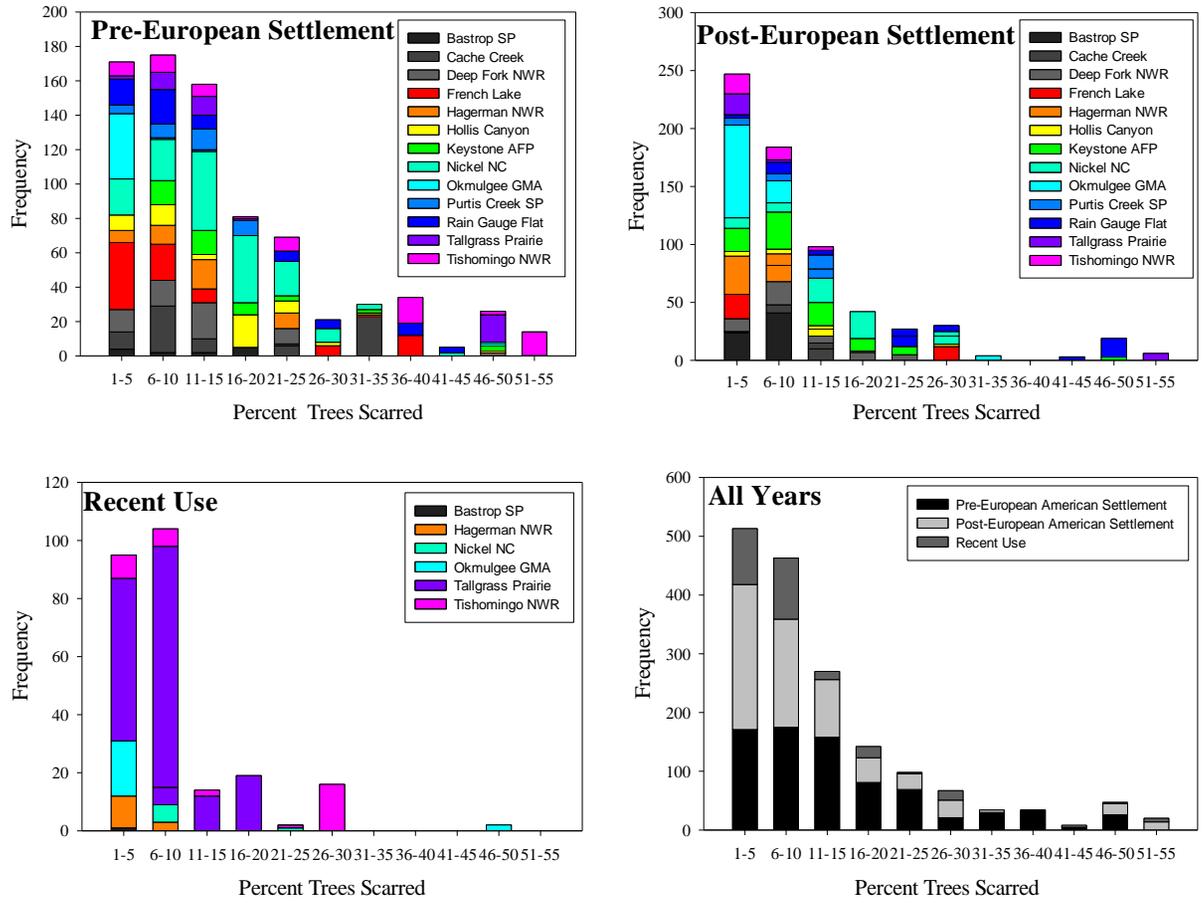
**Figure 8.** Fire scar records across the greater Cross Timbers region during the period 1636-2015 CE. Site names (right side) correspond to site map (Figure 2). Horizontal lines represent the periods of record of each site (i.e. all trees combined). Fire scar dates at bottom represent the occurrence of fire events across the study region. The recorder depth line graph shows the number of sites recording fire through time, while the % sites scarred bar graph shows the percentage of sites recording fire at individual fire events through time.

In the Pre-EAS period, the average number of fire intervals was 30 intervals per site. The length of fire intervals in this period ranged from 1 to 53 years, with the smallest range observed at Tishomingo NWR (1-11 years), and the largest range observed at Cache Creek (1-53 years, Table 3). The average MFI for all sites in this period was 5.19 years, calculated as an average of the MFIs across all thirteen sites (Table 3). The lowest MFI for this time period was observed in eastern Oklahoma at the Nickel Family Nature and Wildlife Preserve (2.95 years), while the highest MFI was observed in southcentral Texas at Bastrop State Park (10.9 years, Table 3).

In the Post-EAS period, the average number of fire intervals was 22 intervals per site. The length of fire intervals in this period ranged from 1 to 66 years, with the smallest range observed in northeastern Oklahoma at the Nickel Family Nature and Wildlife Preserve (1-4 years), and the largest range observed in southwestern Oklahoma at Cache Creek in the Wichita Mountains (2-66 years, Table 4). The average MFI for all sites in this period was 6.78 years, calculated as an average of the MFIs across all thirteen sites (Table 4). The lowest MFI for this time period was observed in central Oklahoma at Okmulgee GMA (1.67 years), while the highest MFI was observed in southwestern Oklahoma at Cache Creek in the Wichita Mountains (19.25 years, Table 4).

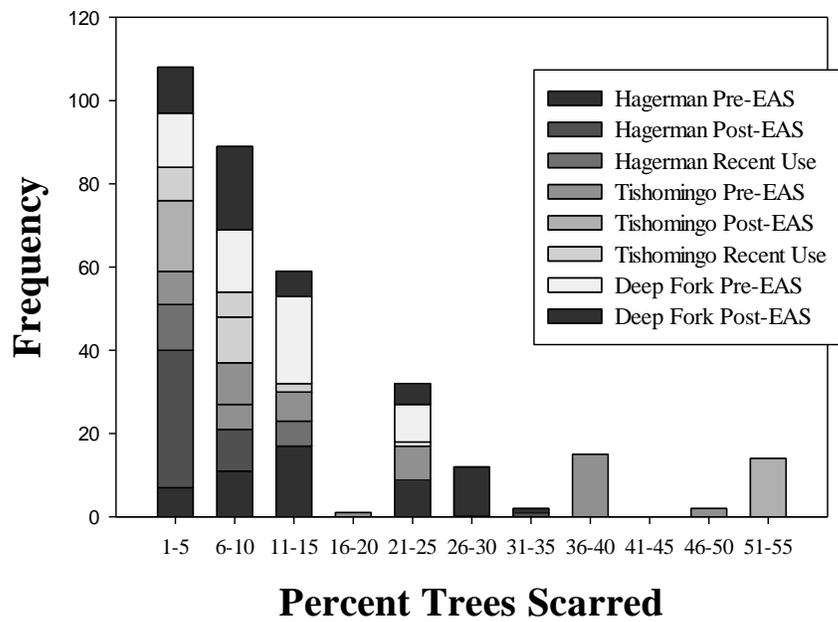
Finally, in the Recent Use period, only six sites were included in this data stratification due to land-use at the individual site level (Table 5). In this period, the average number of fire intervals was 15 intervals per site. The length of fire intervals in this period ranged from 1 to 30 years for all sites, with the smallest range observed in central Oklahoma at Okmulgee GMA (1-2 years), and the largest range observed in southcentral Oklahoma at Tishomingo NWR (1-24 years, Table 5). The average MFI for

all sites in this period was 5.08 years, calculated as an average of the MFIs across these six sites (Table 5). The lowest MFI for this time period was observed in northcentral Oklahoma at Tallgrass Prairie Preserve (1.25 years), while the highest MFI was observed in eastern Oklahoma at the Nickel Family Nature and Wildlife Preserve (16.75 years, Table 5).



**Figure 9.** Frequency distributions of percentages of trees for study sites across the greater Cross Timbers region during the period 1636-2015 CE stratified by three time periods and compiled for all sites in all years.

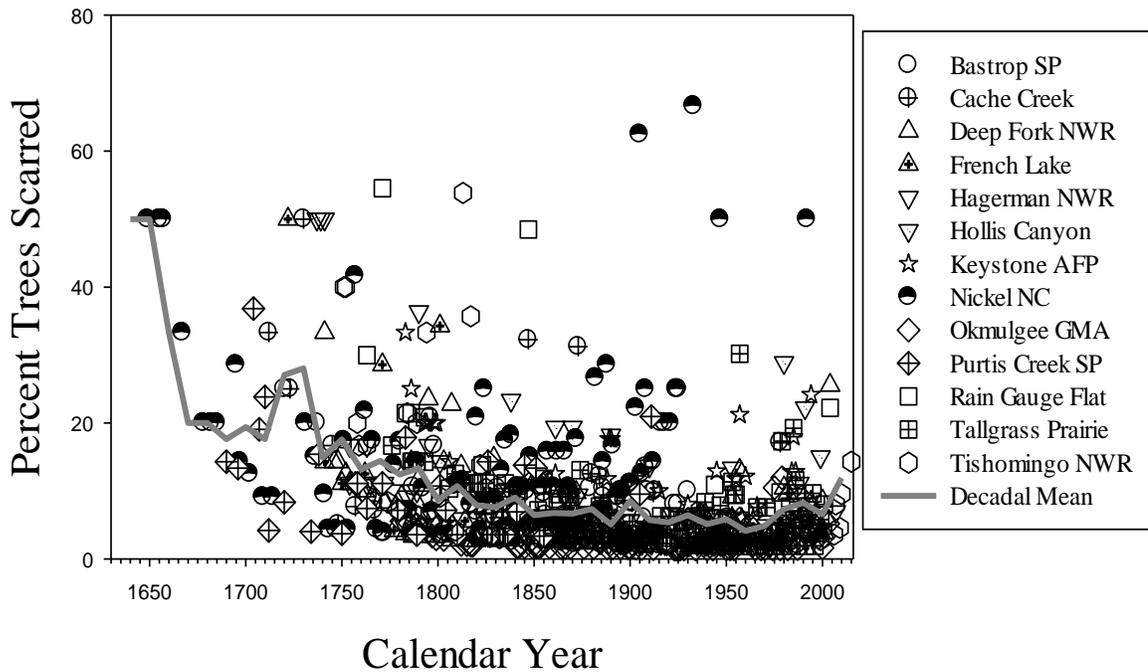
Low severity fires (here defined as  $\leq 5\%$  trees scarred in a fire event) were the most common across all sites and considering all fire event years (Figure 9). This statement also holds true for three new sites- low severity fires were the most common for all years at Deep Fork NWR, Hagerman NWR, and at Tishomingo NWR (Figure 10). From the beginning of the recorded period, fire severity has trended downward through time (Figure 11).



**Figure 10.** Stacked frequency distribution of percentages of trees scarred during fire events for three study sites in the Cross Timbers Region stratified by three time periods.

In the common period (1770-2002), there were four years that recorded fire at eight of the thirteen sites, the highest number of sites that recorded any fire events: 1838, 1870, 1940, and 1953. When examining sites individually for years in which fire at the site was recorded by the most trees, Bastrop State Park had six years in which five trees were recording fire: 1796, 1879, 1886, 1909, 1913 and 1930. At Cache Creek, there were two years in which ten trees recorded fire: 1847 and 1873. At Deep Fork NWR, in 2004,

there were twelve trees recording fire. At French Lake, there was one year- 1801- where twelve trees recorded fire. At Hagerman NWR, six trees recorded fire in 1910. At Hollis Canyon, a fire in 1980 was recorded on thirteen trees. At Keystone Ancient Forest Preserve, there were three years in which seven trees recorded fire: 1957, 1985 and 1994. At Nickel Family Nature and Wildlife Preserve, ten trees were scarred during a fire event in 1757. At Okmulgee Game Management Area, eight trees recorded fire in 1979. At Purtis Creek State Park, nine trees recorded fire in 1911. At Rain Gauge Flat, sixteen trees recorded fire in 1847. At Tallgrass Prairie Preserve, sixteen trees recorded fire in 1957. At Tishomingo NWR, fourteen trees recorded fire in 1813.



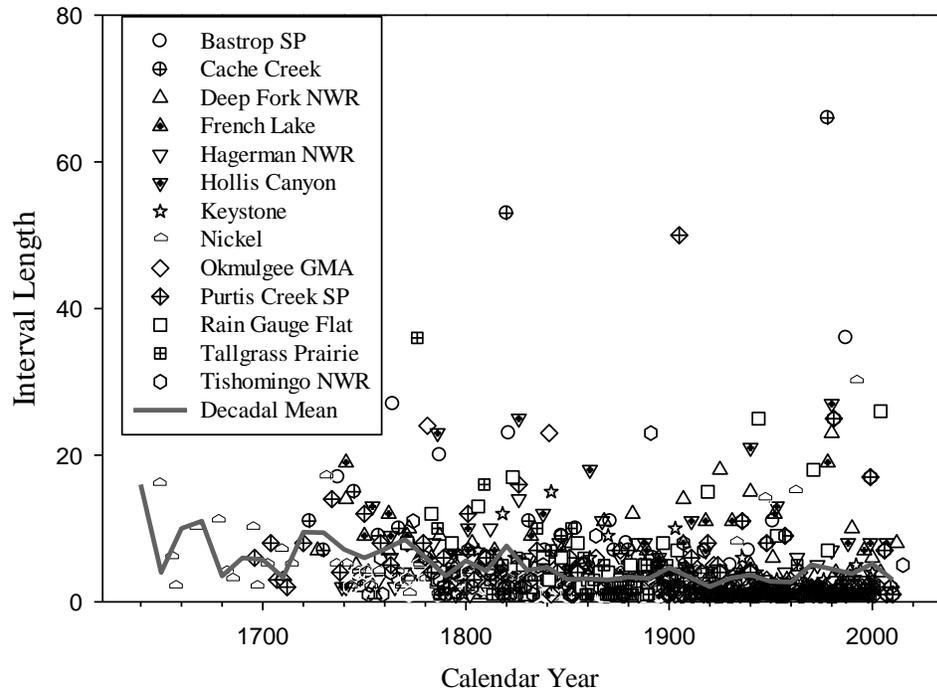
**Figure 11.** Percent trees scarred across the greater Cross Timbers region during the period 1636-2015 CE. Symbols correspond to individual sites while the solid grey line corresponds to the decadal mean plotted through time.

Fire frequency results were not consistent across all thirteen sites. The four northern-most study sites (Tallgrass Prairie Preserve, Keystone Ancient Forest Preserve, Nickel Family Nature and Wildlife Preserve and Okmulgee Game Management Area) all experienced an increase in fire frequency following EAS (Tables 3-5). Twenty kilometers south of Okmulgee GMA, Deep Fork NWR existed in a grouping of study sites that recorded less fire in the post-EAS period, along with Cache Creek, French Lake, Hollis Canyon, Rain Gauge Flat and Tishomingo NWRs. Across the border into Texas, both Hagerman NWR and Bastrop State Park observed an increase in fire frequency following the pre-EAS period, while Purtis Creek State Park observed less fire following EAS. It should be noted that both Purtis Creek State Park and Bastrop State Park experienced a long duration of fire suppression in the latter part of the 20<sup>th</sup> century. When examining fire at the regional level, there were only ten years where no fire was recorded during the common period (1770-2002), none of which occurred in the 20<sup>th</sup> century. Fire was slightly more frequent at this scale following EAS as no years in this period had no years in which no fire was recorded at any of the thirteen fire history sites.

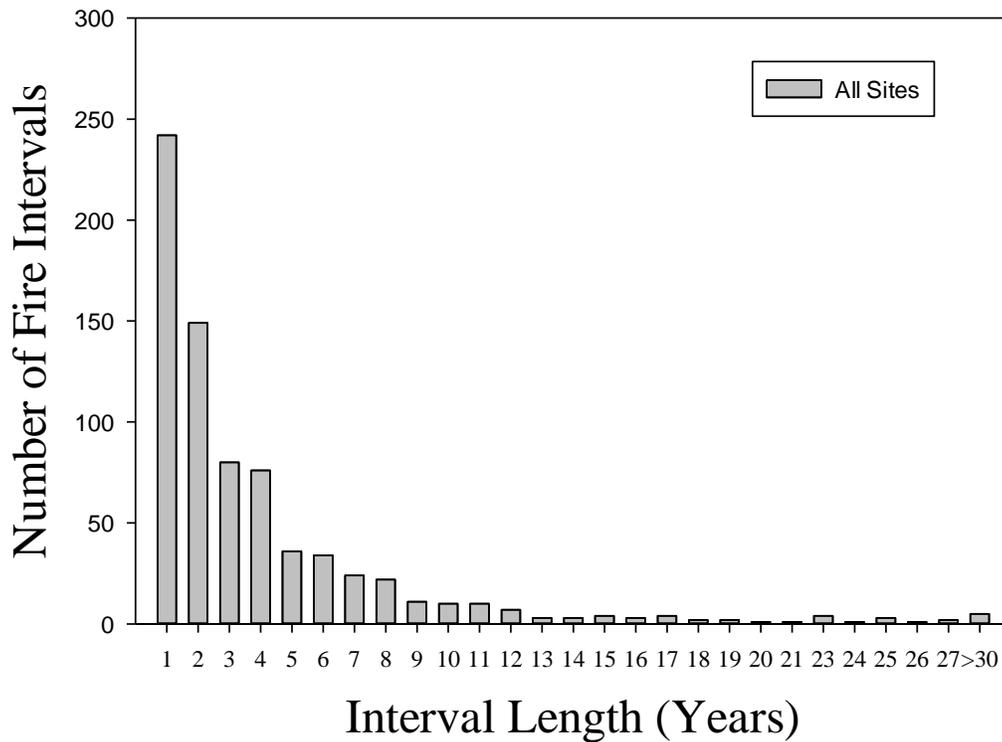
All sites were dominated by dormant season fires, with the range of dormant season fires from 58-97% across all years (Table 2). Growing season fires ranged from 0-21% when considering all years (Table 2). No growing season fires were recorded for either Hollis Canyon, located in southwestern Oklahoma in Wichita NWR, or Purtis Creek State Park in central Texas (Table 2). Bastrop State Park, the southern-most site, recorded more growing season fires than any other site with 21% of the fire scars there recorded during the growing season (Table 2). Among sites, fire scar seasonality was undetermined for a range of 1-36% of fire scars across all years.

### **3.2 Regional Scale Fire History (~140,000 km<sup>2</sup>)**

Fire frequency was also examined at the regional scale by evaluating the fire interval length distribution (Figure 12) across all sites and all years. Fire interval length trended generally downward through time, with a compressed interval period observed between approximately 1850-1900 (Figure 12). One year intervals occurred most frequently among all sites, while longer intervals were much less common among all sites (Figure 13). To consider severity, frequency distributions were used to evaluate the percentage of trees recording fire during a fire event year (Figure 9). When considering all years as well as just the post-EAS period, the majority of fire events were recorded on 1-5% of trees (Figure 9). In both the pre-EAS period and in the Recent Use period, the majority of fire events are recorded on 6-10% of trees (Figure 9).

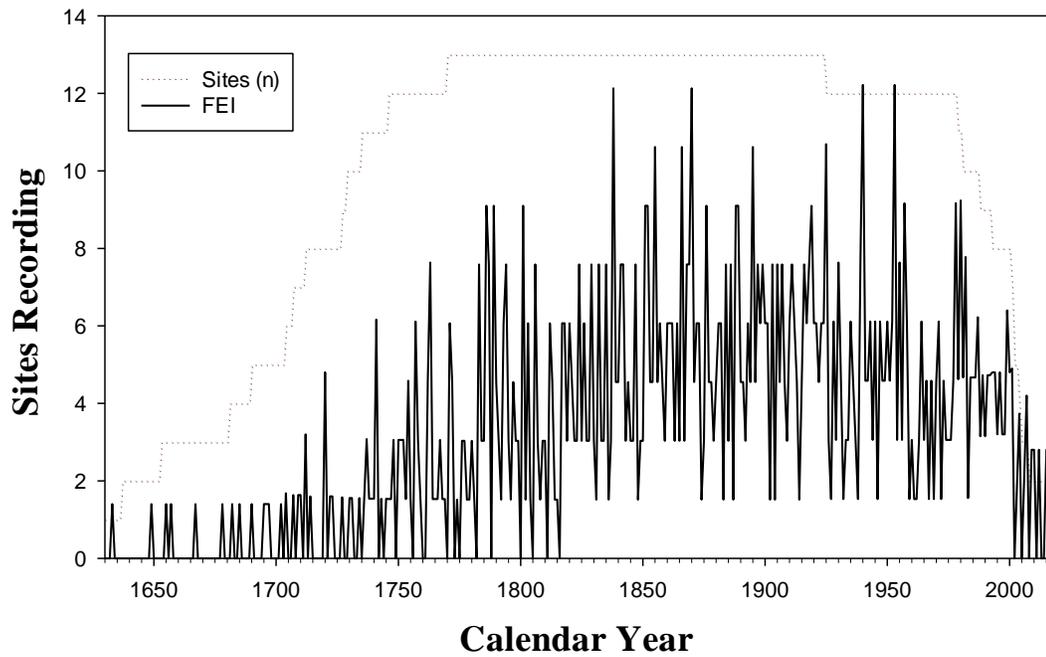


**Figure 12.** Fire intervals of thirteen study sites across the greater Cross Timbers region during the period 1636-2015 CE. Symbols correspond to individual sites while the solid grey line corresponds to the decadal mean plotted through time.

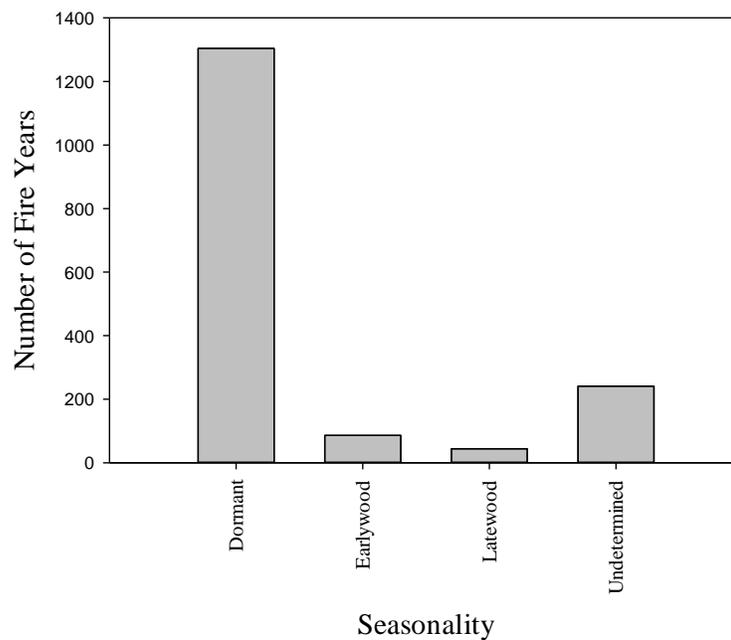


**Figure 13.** Fire interval frequency distribution based on thirteen sites across the greater Cross Timbers region during the period 1636-2015 C.E.

The FEI was used to evaluate the extent of fire events at the regional scale across all thirteen sites. The years 1838, 1870, 1940, and 1953 have the highest FEI, when eight sites are recording fire (Figure 14). The ten years in the common period without fire have the lowest FEI value, as no sites are recording fire and 0% of trees are scarred (Figure 14). Fire seasonality was dominated by dormant season fires (Figure 15). Seventy-nine percent of fires were recorded during the dormant season (Figure 15). Growing season fires (earlywood and latewood fire events combined) constituted 7% of fire scars. Seasonality was undetermined for 14% of all fire scars (Figure 15).



**Figure 14.** Fire Extent Index (FEI) across the greater Cross Timbers region during the period 1636-2015 CE. The FEI is calculated by multiplying the number of study sites in the analysis in that year by the percentage of study sites recording fire. Number of sites in the analysis (recording depth) represented by a dotted line.



**Figure 15.** Fire scar seasonality for thirteen study sites across the greater Cross Timbers region during the period 1636-2015 C.E.

Fire events were 2-7 times more frequent when considered at a regional scale (here defined as ~140,000 km<sup>2</sup>, Table 2) compared to individual sites. When considering all sites in the common period (1770-2002), the MFI was 1.04 years with a range of 1-2 years, as all but 10 fire years had at least one site recording fire. In the pre-EAS period from 1770-1877 (the beginning of the common period to the average end of the pre-EAS period), the MFI was 1.08 years with a range of 1-2 years. During the post-EAS period (the average end of the pre-EAS period to the end of the common period), fire is most frequent with a MFI of 1.0 years. Fire severity (here represented by percentages of trees scarred), however, was highest for the pre-EAS period (1770-1877) where the greatest number of fire events were recorded on 6-10% of trees.

## **4. Discussion**

### **4.1 Fire Regimes of the Cross Timbers**

The Cross Timbers ecoregion is of special interest as one of the largest tracts of uncut forest in the U.S., and there is evidence that the historical landscape was impacted by fire through its influence on both vegetation structure and composition for at least the past 5000 years (Therrell and Stahle 1998, Hoagland et al. 1999, Anderson 2006). In this region, the role of fire is still being defined (Wright and Bailey 1980). Human interactions with both fire and vegetation vary with human density and alterations in human culture (Guyette et al. 2002, Clark et al 2007, DeSantis 2010, Stambaugh et al. 2014). Findings here suggest that while fire frequency has increased following EAS, fire

severity has trended downward-reflecting fuel-fragmentation, and increased land-use changes across the region.

## **4.2 Fire Frequency**

Site differences in fire frequency existed across the greater Cross Timbers region. The four most northern sites in Oklahoma (Tallgrass Prairie Preserve, Keystone Ancient Forest Preserve, Nickel Family Nature and Wildlife Preserve, and Okmulgee Game Management Area) underwent an increase in fire frequency following EAS. Oklahoma sites to the south (Deep Fork NWR, all sites at Wichita NWR and Tishomingo NWR) all observed a decrease in fire frequency following EAS. In Texas, the three sites were variable, with Purtil State Park observing a decrease in fire following EAS, and Hagerman NWR and Bastrop State Park observing an increase in fire frequency following EAS. With sites in close geographic proximity exhibiting comparable fire regime trends, the findings suggest that there is a relationship between fire regime trends and geography. Another possible explanation is a dichotomy in Oklahoma between northern and southern sites due to differences in historical land-use.

At Tallgrass Prairie Preserve in northern Oklahoma, there is evidence for historical burning by cattle producers as early as 1923 (Hensel 1923). A similar management has continued at Tallgrass Prairie Preserve until the present day (Allen et al. 2011). At Okmulgee GMA, there is evidence that an increase in human occupation after 1900 at the site initiated more frequent burning (DeSantis et al. 2010). At Keystone Ancient Forest Preserve in northcentral Oklahoma, the increased fire frequency was

attributed to an increased population following statehood, again attributing an increase in fire frequency to increased human population density (Clark et al. 2007).

Fire history sites at both Tishomingo NWR and Wichita NWR are in close proximity to forts established by the U.S. government. Fort Washita, 8 km from Tishomingo NWR (established in 1842) and Fort Sill, 30 km from Wichita NWR (established 1869) were both hubs of human activity, and their establishment led to increased human occupation and grazing in the vicinity (Wittry 1961, National Register Properties in Oklahoma, 2017). Based on the data presented here, fire occurrence decreased following the establishment of these forts. Grazing has known impacts on fuel reduction and fuel fragmentation, can encourage fire suppression by increasing concerns for losses of animal forage (Touchan et al. 1995, Courtwright 2007), and may be one explanation of a decrease in fire frequency at the southern Oklahoma sites. The inconsistency in fire occurrence findings at Texas sites may also be influenced by a history of grazing in the state, although the geographic relationship between Texas sites in the study is less apparent. At Bastrop State Park, EAS included increases in human population and open range razing (Stambaugh et al. 2017), although no history of grazing is known at either Hagerman NWR or Purtil Creek State Park.

#### **4.3 Fire Severity**

While frequency of fire at the regional scale increased following EAS, fire severity decreased across the region. At individual sites, Tallgrass Prairie Preserve, the Keystone Ancient Forest Preserve, and the Wichita NWR all observed lower percentages of trees scarred in the post-EAS period than in the pre-EAS period (Clark et al. 2007,

Stambaugh et al. 2009, Allen et al. 2011). This result may indicate that there has been a restriction on fire's ability to spread in this time period. Alternatively, this result could indicate that these fires were grass-fueled wildfires, which tend to scar less trees in comparison to fires burning through woody fuels which may have a longer fire duration and produce more fire scars. Still, another possibility is that high frequency of fires at a site could reduce fuel loads, resulting in a reduction of fire duration and fire scars recorded at the site.

Human developments such as roads, railroads, state borders, divisions of public/private lands, and passageways for domesticated livestock all contribute to the division and fragmentation of the landscape and fuels. Guyette et al. (2002) refers to this stage as "fuel fragmentation"- when regional trade, roads, railroads, and markets allow for the increase of human population density and artificial fuel breaks (Guyette et al. 2002). Results from other research in the greater Cross Timbers region also suggests this land-use in the region may have influenced fire severity (Clark et al. 2007, DeSantis et al. 2010, Allen et al. 2011). This pattern of regional disruption of fuels due to human impediments is certainly plausible in the Cross Timbers region.

#### **4.4 Fire Extent**

The FEI was used to evaluate the extent of fire events at the regional scale across all thirteen sites. The years 1838, 1870, 1940, and 1953 had the highest FEI, when eight sites recorded fire. Eighty-six percent of fire years in the common period between all sites (1770-2002) are shared between at least 2 sites, although the geographic relationship between shared fire years was not considered. In Stambaugh et al. (2013), results showed

that fire years at Nickel Family Nature and Wildlife Preserve were similar to fire history sites in the central and western Ozark region of Arkansas and Missouri (Guyette et al. 2006); the repeatability here suggested regional extensity was attributed to drought conditions and a similarity between anthropogenic influences from Native American peoples in that region of the U.S. (Stambaugh et al. 2013). The high repeatability of fire years between at least two sites in the greater Cross Timbers region may suggest a similar relationship, although a further examination of the role of drought and geographic similarity in the region should be conducted to draw these conclusions out.

#### **4.5 Fire Seasonality**

The results of this study indicate a prevalence for dormant season fires across the greater Cross Timbers region. The main lightning season in this region is in the growing season (summer) (Holle and Cummins 2010) and the low occurrence of recorded growing-season fires in the study indicates that lightning has not been the leading cause of fire occurrence. A possible exception in the greater Cross Timbers region is Bastrop State Park where 21% of fires were recorded in the growing season. Bastrop State Park is the southern-most site, where growing-seasons, and potentially fire seasons, are longer than at other sites in the study (Stambaugh et al., 2017).

#### **4.6 Drivers of Spatial and Temporal Variability**

Based on the compilation of fire history data in this study, there may be evidence that fire events found in this region are or have been impacted by the frequent occurrence of drought in the Cross Timbers (Stahle et al. 1985). A number of site-level studies have

not observed a relationship between fire occurrence and drought in the Cross Timbers (DeSantis et al. 2010, Allen et al. 2011). Other studies, however, have found this relationship (Clark et al. 2007, Stambaugh et al. 2009). The ambiguity of these conclusions across the region implies that there is disparity between sites recording fire and the influence of drought. Many fire history studies cover small areas (e.g. 1 km<sup>2</sup>), which may not allow for the detection of the spatial-temporal variability of fire regimes at the landscape to regional scale (Swetnam and Baisan 1996, Stambaugh and Guyette 2008, Stambaugh et al. 2016). There is motivation, then, to further evaluate the relationship between drought and fire occurrence, at a scale larger than is typical for individual fire history study-sites.

#### **4.7 Management Implications**

New fire history site reconstructions and regional fire analyses were supported by the National Wildlife Refuge System. Many management efforts on these properties rely on ecological research to guide policies and management. Historical fire history data can guide in the understanding of historical vegetation conditions where historical conditions are the desired outcome from prescribed burning (Swetnam et al. 1999). The heterogenous role of fire on the landscape often leads to questions related to fire regime characteristics. Fire planning and prescriptions can cover hundreds to thousands of hectares, and it is therefore necessary to evaluate the spatial and temporal variations across landscapes, and to adapt fire management strategies accordingly. Modern policies focus ecosystem restoration efforts on prescribed burning and fuel reduction through mechanical means on millions of hectares and have proposed reintroductions of pre-fire

suppression fire regimes (USDA and USDI, 2002). Fire management planning contains some aspects that are spatially dependent. This study demonstrates scale dependence from site regional scales.

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## CHAPTER THREE

### Historical Fire Synchrony and Climate in the Cross Timbers of Oklahoma and Texas, United States

#### 1. Introduction

Wildfire events have gained public attention in recent years, due to an increase in occurrence and size, with 2006 and 2011-2012 recording some of the most active wildfires on record in the southcentral United States. A concern over wildfire occurrence, and its relationship to drought and a changing climate has brought increased focus to the interface between the public and fire (Scasta et al. 2016). Multiple factors, including an increase in fuel loading from decades of continuous fire suppression, changes in land use and ownership, and management strategies are dampening the success of wildfire suppression rates in some ecosystems (Covington and Moore 1994, Allen et al. 2002). Wildfire occurrence is influenced by many factors ranging from drought and climate oscillations at the regional level to fuel availability and land-use at the site level (Falk et al. 2007, Gill and Taylor 2009, Yocum et al. 2017).

Local influences such as fire ignition, topography, and fuel availability impact fire occurrence (Falk et al. 2007, Gill and Taylor 2009). Topography and elevation at the site level can influence how climatic trends like drought are expressed on the landscape (Giorgi et al. 1997, Rupp et al. 2016). Both topography and elevation work together with other local controls to influence fire occurrence by controlling the microclimate and fuel continuity available (Heyerdahl et al. 2001). When fire occurrence differs across a region, then local influences may be impacting fire ignition and spread (Falk et al. 2011). Regional controls, in contrast, can influence fire occurrence by affecting moisture patterns, and thus the vegetation and structure of fuels available for fire events. On a

regional scale, both drought and climate oscillations influence regional fire activity (Dai et al. 1998, Scasta et al. 2016). The interactions between local and regional influences show up in a number of ways- including in an increased production of fine fuels during periods of enhanced moisture, (Swetnam and Betancourt 1998, Veblen et al. 2000, Brown and Wu 2005). Through these pathways, synchronous fire occurrence at spatially separate sites can result from the influences of climate on the larger landscape (Heyerdahl et al. 2001).

Fire occurrence does not act independently of climate, but instead as a product of its interactions with local and regional weather and climatic patterns that have changed over time. Research from across the continent supports this claim, including in the southwestern United States (Swetnam and Baisan 1996, Grissino-Mayer and Swetnam 2000), the Pacific Northwest (Heyerdahl et al. 2008), the southcentral U.S. (Stambaugh et al. 2011), and California (Taylor et al. 2016). Across the western U.S., large-scale patterns of climate influence the synchronous occurrence of fire (Kitzberger et al. 2007, Falk et al. 2011). Results from Grissino-Mayer and Swetnam (2000) suggest a link between long-term regional scale changes in both precipitation patterns and fire regimes in northwestern New Mexico. In the Pacific Northwest, Heyerdahl et al. (2008) found that, while inter-annual variation in climate was a strong driver of regionally synchronous fires, larger-scale climate patterns like the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) were weak drivers of more regionally synchronous fires. In Swetnam and Baisan (1996), both fuels and climate were found to be the primary controls of fire regimes. Here, drought conditions prevailed in the largest fire years- where synchrony was observed across the study region. Climate and fire history

reconstructions from tree-ring analyses show that climate has been influencing the occurrence of fire across North America for many centuries, but humans have constrained the fire-climate relationship through sociological processes that have affected the relationship between fuels, fire, and climate (Taylor et al. 2008, Marlon et al. 2012, Taylor et al. 2016).

Both models and observations show that Pacific sea surface temperatures (SSTs) are important drivers of temperature and moisture patterns across the southcentral United States. For this region, patterns are most closely related to oceanic-atmospheric processes of both the central and subtropical Pacific region (Swetnam and Betancourt 1990). Through time, alterations of SSTs in the Pacific region influence the fluctuation of moisture in the troposphere (Sheppard et al. 2002). These alterations result in precipitation pattern shifts at high-frequency inter-annual time scales such as the ENSO (Grissino-Mayer and Swetnam 2000). The ENSO is an aperiodic occurrence that reoccurs every 2-7 years and alternates between two extremes- called El Niño and La Niña. Once it begins, the phase (El Niño and La Niña) lasts for 18-24 months (Philander 1985, Yasunari 1985, Allan et al. 1996). Although the climatic patterns that drive either the La Niña or the El Niño are often opposite, each El Niño or La Niña varies in its behavior (i.e. duration, extent) (Ropelewski and Halpert 1987, Kiladis and Diaz 1989, Allen et al. 1996). During El Niño events, warming of the tropical regions of the Pacific and Indian Oceans displaces the rainfall-producing systems from the continents to these ocean regions, altering climatic regimes. During La Niña events, the opposite movement occurs, cooling the tropical regions of the Pacific and Indian Oceans (Webster 1994, Allen et al. 1996). In general, La Niña events cause dry conditions in the southwestern

U.S. (Trenberth et al. 1988, D'Arrigo and Jacoby 1991, Westerling and Swetnam 2003). During these events, colder ocean waters are present in the tropical Pacific due to strengthening trade winds. This process encumbers rainfall, bringing dry conditions to the southwestern United States, including the Cross Timbers region of Oklahoma and Texas (Cook et al. 2000). In contrast, El Niño events have an association with increased moisture.

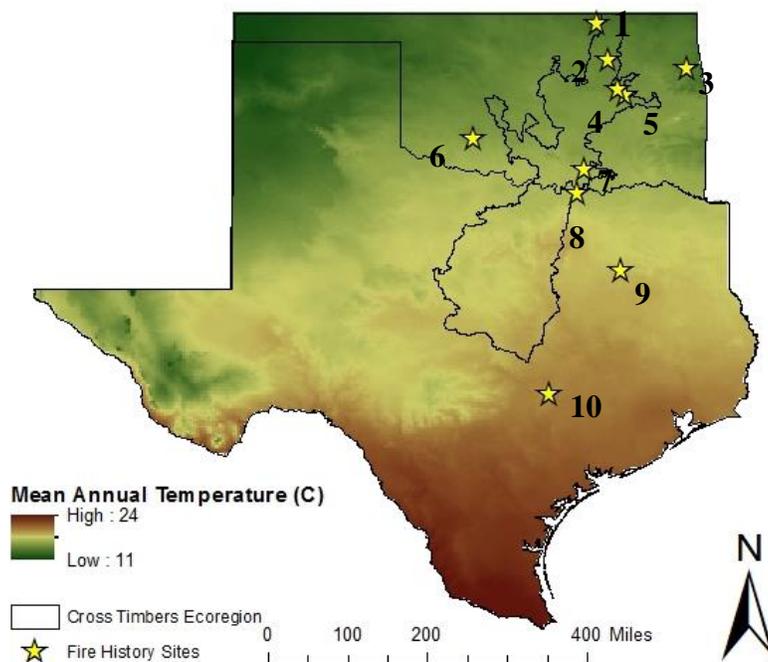
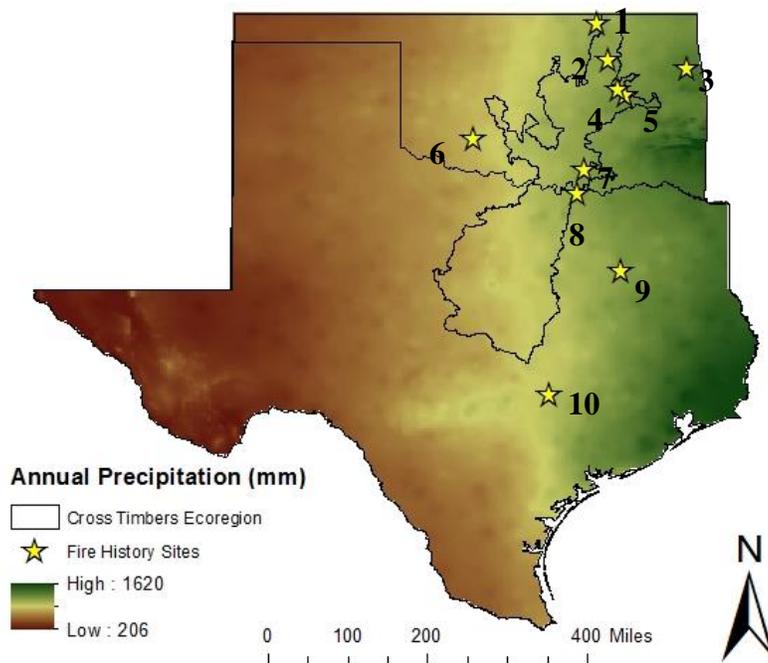
Some of the strongest ENSO signals yet detected in any tree-ring data worldwide are in post oak chronologies of Texas and Oklahoma (Turney 2003). Little is known about how the role of climate differs in driving fire occurrence at the site to regional scale. In this region, many studies have attempted to explore how climate drives fire at the site level, but inconsistencies in the results of these studies leave questions about the comparability of these conclusions, and the role of climate in altering climate activity at the regional scale. My goal was to assess the relationship between climate patterns on fire occurrence in the southcentral U.S. I wanted to evaluate the independent and interactive influences of drought and the ENSO on fire occurrences at both site and regional levels. I hypothesized that at the individual fire history site level, conditions other than climate would be the best predictor of fire occurrence, while at the regional level, larger-scale climate patterns such as drought and the ENSO would be drivers of regionally synchronous fires. Further, I expected that fire history sites found in geographically similar locations would be more similar in their years of fire occurrence than geographically disparate sites.

## **2. Methods**

### **2.1 Study Region**

The Cross Timbers ecoregion in southcentral U.S is a patchwork of forest, savanna, and prairie, between the eastern deciduous forest and Great Plains prairie ecosystems (Kuchler 1964). The Cross Timbers is described by gradients in both precipitation and temperature (Figure 16). The Cross Timbers run in a generally North-South direction across more than 72,000,000 hectares that includes portions of southern Kansas, eastern Oklahoma, western Arkansas, and north central Texas. Annual temperatures range from 15°C in the northern-most region to 18.8°C in the south. Average annual precipitation varies from 102 cm in the east to 71 cm in the west (Hoagland et al. 1999). Precipitation is well distributed throughout the year with a maximum in May. Wide swings in annual precipitation can result in severe and prolonged droughts across the region (Arndt 2011).

In the Cross Timbers, drought occurs at approximately 20-year intervals (Rice and Penfound 1959, Johnson and Risser 1975). Extended droughts, up to a decade long, have been a consistent climate feature of the southcentral U.S. since at least the 800's (Cleaveland et al. 2011). Stahle and Hehr (1984) demonstrated that chronologies of post oak show more sensitivity to climate westward toward the prairie boarder- consistent with decreased rainfall, forest cover, species diversity, and overall tree size.



**Figure 16.** Oklahoma and Texas 30-year normals of annual precipitation in millimeters (top, Daly et al. 2004) and annual mean temperature in Celsius (bottom, Daly et al. 2004). The Cross Timbers Ecoregion is delineated in black. Fire history (yellow stars) represent a common time period of fire occurrence data from 1770-2002. 1: Tallgrass Prairie Preserve 2: Keystone Ancient Forest Preserve 3: Nickel Family Nature and Wildlife Preserve 4: Okmulgee Game Management Area 5: Deep Fork National Wildlife Refuge 6: Wichita National Wildlife Refuge 7: Tishomingo National Wildlife Refuge 8: Hagerman National Wildlife Refuge 9: Purtil Creek State Park 10: Bastrop State Park.

## **2.2. Fire Occurrence Data**

### **2.2.1. Historical Fire Event Data**

Thirteen datasets of fire scar events were used to address climate and fire across the greater Cross Timbers region (Table 6, Figure 16, Figure 17). These sites allowed us to better evaluate the significance of results, and expand understanding of fire occurrence from individual sites to regional scales. Because there are differences in both annual precipitation and annual mean temperature in the Cross Timbers region from north to south, sites were arranged and examined along this gradient (Figure 16, Hoagland et al. 1999, Daly et al. 2004). Site data were provided by authors of publications with similar study areas and sampling methods. The Nature Conservancy's Tallgrass Prairie Preserve was sampled to study the largest protected area of tallgrass prairie in North America (The Nature Conservancy, Table 6). Here, there was no strong relationship between fire and climate found in the years surrounding a fire event, attributed here to the high number of fire events observed at the site (Allen and Palmer 2011). The Nature Conservancy's Keystone Ancient Forest Preserve lies in the northern Cross Timbers ecoregion in southern Osage County, and is characterized as old-growth due to the presence of post oak and eastern red cedar trees greater than 300 and 500 years old, respectively (Table 6, Therrel and Stahle 1998). At the KAFP, there was a concurrence of both moderate and large-scale fire events within the site during periods of below normal Palmer Drought Severity Index (PDSI) values (Clark 2007). The Nickel Family Nature and Wildlife Preserve is located in the Ozark Highlands of eastern Oklahoma and has a strong component of shortleaf pine (*Pinus echinata*, Table 6). Here historical fire years were

slightly more common in dry years, and years with fires occurring throughout the study area were synchronous with regional droughts (Stambaugh et al. 2013). The Okmulgee Game Management Area (OGMA), located in central Oklahoma, is composed of primarily upland post oak and blackjack oak (Table 6). At OGMA, no significant relationship was detected between fire occurrence and PDSI (DeSantis et al. 2010). The Wichita Mountains Wildlife Refuge (WMWR) includes four fire history sites each separated by up to 6 km within the refuge (Cache Creek, French Lake, Hollis Canyon and Rain Gauge Flat, Table 6). Here, conditions were significantly drier in the year of fire events, or during the preceding 2 years (a lag of 1 or 2 years, Stambaugh et al., 2014). Further south, Purtil Creek State Park is located in northern Texas, at the grassland-woodland transition zone at the southern periphery of the tallgrass prairie ecosystem (Table 6). Although a fire history record was reconstructed, no climate analysis was done (Stambaugh et al., 2011). Lastly, Bastrop State Park (BSP), in southcentral Texas, no relationship was found between drought and fire occurrence or drought and percent trees scarred at the site (Stambaugh et al., 2017).

For each study site, fire event data were summarized for entire periods and for three different sub-periods corresponding to: pre-European American Settlement (pre-EAS), post-European-American Settlement (post-EAS), and Recent Use. Sub-periods were chosen based on regional documented changes in land uses. For each study site, the timing of these sub-periods differed by site. When available, time period breakdowns were maintained from original publications (Table 7).

**Table 6.** Fire history study site summary information stratified for the greater Cross Timbers region.

<b>Site Name</b>	<b>Date Range</b>	<b>Number of Samples</b>	<b>Number of Fires</b>	<b>Species</b>
<b>Tallgrass Prairie Preserve</b>	1729-2005	54	242	Post Oak
<b>Keystone Ancient Forest Preserve</b>	1770-2002	51	138	Post Oak, Blackjack Oak, Shumard Oak, Black Hickory
<b>Nickel Family Nature Center and Wildlife Preserve</b>	1639-2005	34	205	Shortleaf Pine
<b>Okmulgee Game Management Area</b>	1690-2008	69	172	Post Oak
<b>Deep Fork NWR</b>	1703-2016	49	115	Post Oak
<b>Rain Gauge Flat</b>	1746-2009	46	102	Post Oak
<b>Hollis Canyon</b>	1720-2010	46	105	Post Oak
<b>French Lake</b>	1700-2005	54	122	Post Oak
<b>Cache Creek</b>	1636-2010	43	91	Post Oak
<b>Tishomingo NWR</b>	1730-2015	49	112	Post Oak
<b>Hagerman NWR</b>	1701-2015	51	93	Post Oak
<b>Purtis Creek State Park</b>	1681-2005	49	83	Post Oak
<b>Bastrop State Park</b>	1653-2011	50	98	Post Oak
<b>All Sites (Max)</b>	<b>1636-2015</b>	<b>596</b>		
<b>All Sites (Common)</b>	<b>1770-2002</b>	<b>573</b>		

**Table 7.** Fire history study site summary information stratified for the greater Cross Timbers region for four periods: All Years, Pre-European American Settlement, Post-European American Settlement, and Recent Use.

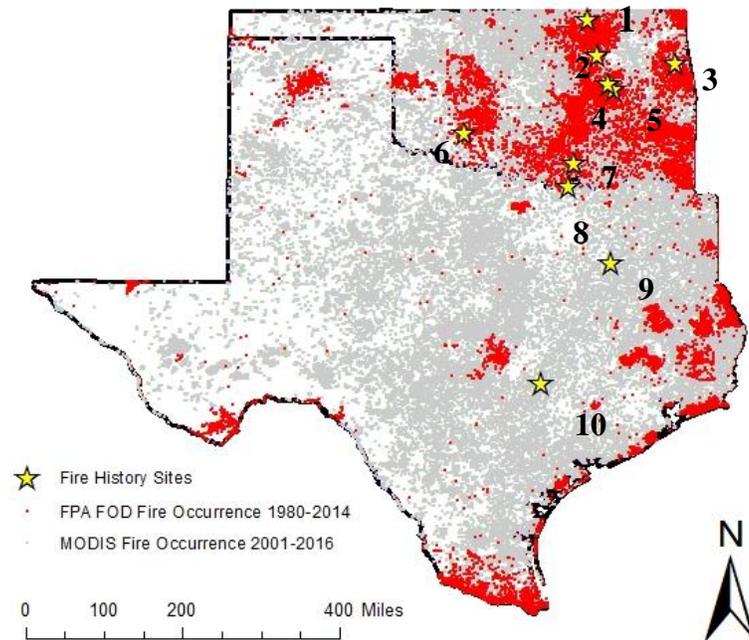
<b>Site Name</b>	<b>All Years</b>	<b>Pre-EAS</b>	<b>Post-EAS</b>	<b>Recent Use</b>
<b>Tallgrass Prairie Preserve</b>	1729-2005	1770-1871	1871-1914	1915-1989
<b>Keystone Ancient Forest Preserve</b>	1770-2002	1772-1907	1908-2001	n/a
<b>Nickel Family Nature Center and Wildlife Preserve</b>	1639-2005	1650-1889	1890-1925	1925-1992
<b>Okmulgee Game Management Area</b>	1690-2008	1750-1899	1900-1988	1989-2005
<b>Deep Fork NWR</b>	1703-2016	1704-1899	1900-2016	1703-2016
<b>Rain Gauge Flat</b>	1746-2009	1746-1899	1901-2008	n/a
<b>Hollis Canyon</b>	1720-2010	1720-1899	1901-2010	n/a
<b>French Lake</b>	1700-2005	1712-1899	1901-2005	n/a
<b>Cache Creek</b>	1636-2010	1637-1899	1901-2010	n/a
<b>Tishomingo NWR</b>	1730-2015	1736-1842	1842-1946	1946-2015
<b>Hagerman NWR</b>	1701-2015	1707-1842	1842-1946	1946-2015
<b>Purtis Creek State Park</b>	1681-2005	1690-1820	1820-1924	n/a
<b>Bastrop State Park</b>	1653-2011	1653-1829	1830-1940	1941-2011

### **2.2.2. Fire Record Data**

Fire scar history data are typically long in temporal resolution, but lack seasonal resolution and high replication. For this reason, we analyzed data from the Moderate Resolution Imaging Spectroradiometer Active Fire Product (MODIS) Active Fire Product from 2011 to 2016 (Figure 17). MODIS data are fire occurrences detected in 1-km pixels that are burning at the time of the satellite overpass under relatively cloud-free conditions (Giglio et al, 2003). MODIS has a global overpass time every 1-2 days, in 36 discrete spectral bands. This data set includes records of active fire locations at the time of overpass based on infrared “heat” signatures. MODIS has several advantages in its use including: overpasses occur both during the day and night, fires are detected at the time of the overpass of the satellite if they are actively burning, and MODIS is quite sensitive in its detection in comparison to other fire detection methods. The dataset has drawbacks and inherent biases as well, namely that clouds have the ability to hide actively-burning fires from detection and that the fires must be actively burning at the time of the overpass (Giglio et al. 2003). Fire sizes of  $\sim 1000 \text{ m}^2$  are regularly detected, and there is no upper limit to fire temperature or size that can be detected. An additional drawback of the dataset is its limited timeframe, as the MODIS Active Fire Product has only been available since 2000, with complete and reliable records beginning in 2001 (Figure 17). In the period from 2001-2016, the MODIS dataset for Oklahoma and Texas includes 196,194 fire records.

Additional fire occurrence data was sourced from the Fire Program Analysis fire-occurrence database (FPA FOD, Figure 17, Short, 2014). This database includes locations of wildfires that occurred in the U.S. from 1980 to 2014. The wildfire database

represents events from the reporting systems of federal, state, and local fire organizations. The dataset is based on geospatial documentary fire records, and has been evaluated for completeness using archival summary records (Short 2014). While this dataset represents a longer time frame (1980 to 2014), the data are more spatially clumped in Oklahoma and Texas due to the nature of the dataset's reporting (Figure 17). The wildfire records were acquired from the reporting systems of federal, state, and local fire organizations. In the period from 1980-2014, the dataset includes 12,629 fire records in Oklahoma and Texas. For both recent fire occurrence datasets, ArcGIS (ESRI 2011) was used to delineate the state boundaries for both Oklahoma and Texas, and to delineate the month in which the fire record occurred. The data were then totaled and averaged per month, to better understand the occurrence of fire, as recorded by either dataset.



**Figure 17.** Fire occurrence data from the Fire Program Analysis Fire Occurrence Database (FPA FOD, Short 2013) fire occurrence data (1980-2014) and Moderate Resolution Imaging Spectroradiometer Active Fire Product (MODIS, 2001-2016, Giglio et al. 2003) for Texas and Oklahoma. Fire history sites (yellow stars) represent a common time period of fire occurrence data from 1770-2002. 1: Tallgrass Prairie Preserve 2: Keystone Ancient Forest Preserve 3: Nickel Family Nature and Wildlife Preserve 4: Okmulgee Game Management Area 5: Deep Fork National Wildlife Refuge 6: Wichita National Wildlife Refuge 7: Tishomingo National Wildlife Refuge 8: Hagerman National Wildlife Refuge 9: Purtil Creek State Park 10: Bastrop State Park.

## 2.3. Climate Data

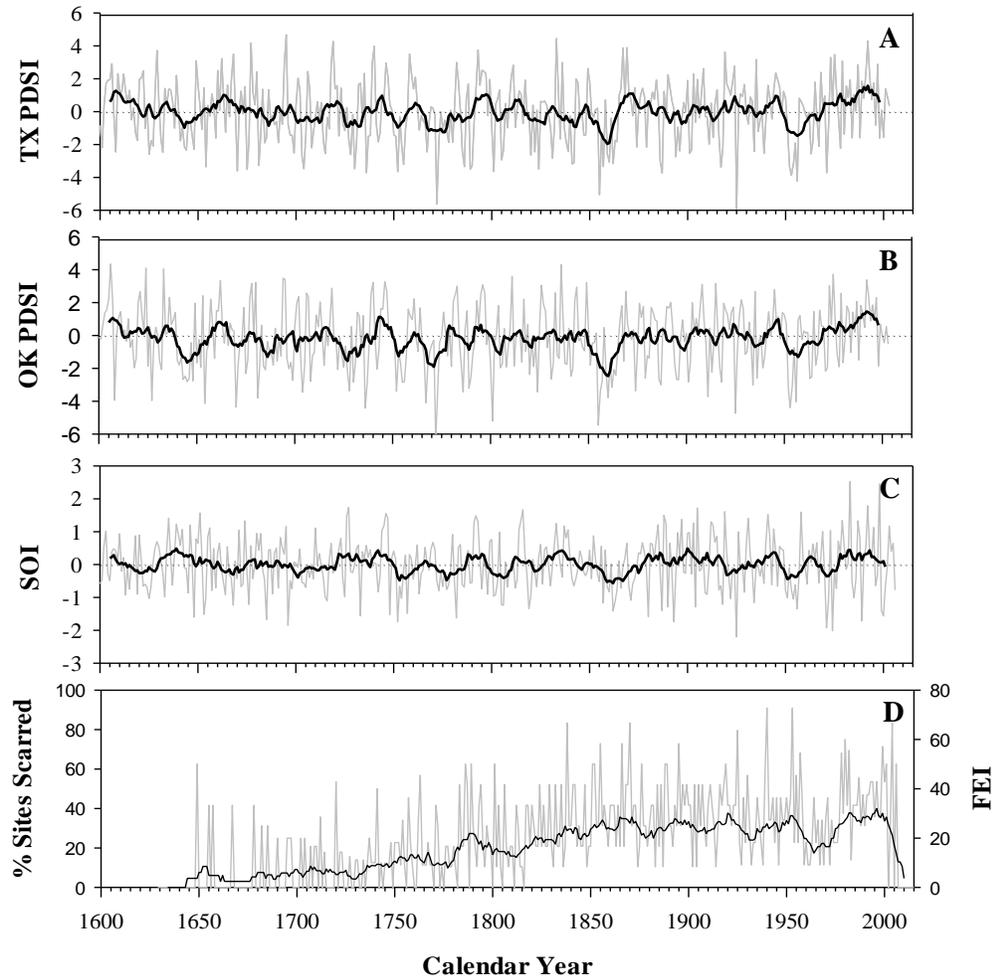
### 2.3.1. Historical Climatic Reconstructions

To evaluate the drought in the region of interest, the reconstructed Palmer Drought Severity Index (PDSI) was used, derived from The North American Drought Atlas (Cook et al. 2004). The PDSI is the most prominent index of meteorological drought used in the U.S., ranging from -10 (dry) to +10 (wet) with values below -3 representing severe to extreme drought (Heim 2002). The PDSI was created by Palmer (1965) to measure the cumulative departure (relative to mean conditions) in atmospheric moisture supply and demand at the surface and incorporates antecedent precipitation,

moisture supply, and moisture demand (Palmer 1965). The Cook et al. (2004) reconstructed PDSI dataset is derived from geographically relevant PDSI grid points from the North American instrumental PDSI grid (accessed at <http://iridl.ldeo.columbia.edu/SOURCES/.LDEO/.TRL/.NADA2004/.pdsi-atlas.html>). This grid has a resolution of 2.5 degrees latitude by 2.5 degrees longitude, patterned after a global study of drought (Dai et al. 1998). The entire grid is composed of 286 grid points covering most of North America and utilizes 835 tree-ring chronologies. The method used to create the grid is based on the assumption that only tree-ring chronologies geographically near to a PDSI grid point are true predictors of drought at that location (Cook et al. 1999). The grid points utilized here were points 193 and 179 in Oklahoma, and points 194 and 195 in Texas, chosen based on the basis of proximity to fire history sites. The average annual PDSI for Oklahoma (OK PDSI) was calculated as the average of two grid points (193, 179, Figure 18). The average annual PDSI for Texas (TX PDSI) was calculated as the average of two grid points (194, 195, Figure 18).

The reconstruction of the ENSO (Figure 18) utilized here is the Cook et al. (2008) SOI reconstruction (available online at: <https://www1.ncdc.noaa.gov/pub/data/paleo/treering/reconstructions/nino-cook2008.txt>). This data set utilized tree-ring data from Mexico and Texas to reconstruct Niño 1+2, 3, 3.4 and 4 indices where negative index values are associated with La Niña conditions and positive index values are associated with El Niño conditions (Ropelewski and Halpert 1986, Kiladis and Diaz 1989). Reconstructions extend back in time to 1300 C.E., with the best verified portion beginning in 1400 C.E. Post-1979 data in the Cook et al. 2008 record are instrumental. In this study, PDSI data utilized spanned 1600-2006 C.E.; the

common period for the thirteen fire history sites spanned 1700-2002 and the longest site-specific fire history record spanned 1637-2009 (Cache Creek). The Cook et al. (2008) reconstruction was chosen for its geographic similarity to the fire history study sites. Historically, the ENSO has been classified based on the intensity of SST anomalies in a certain region of the equatorial Pacific. Here, reconstructions of Sea Surface Temperatures (SSTs) in the Niño 3.4 region was used, selected because it is the most commonly used region, and encompasses the western half of the “equatorial cold tongue region” and provides a better measure of important changes in both SSTs and SST gradients (Figure 18).



**Figure 18.** Reconstructions of (A) Texas Palmer Drought Severity Index (PDSI, grey line) and 11-moving average (black line) (B) Oklahoma Palmer Drought Severity Index (PDSI, grey line Cook et al. 2004) and 11-year moving average (black line) (C) the Southern Oscillation Index (SOI, grey line Cook et al. 2008) and 11-year moving average (black line) (D) 11-year moving average of percent fire history sites scarred (black line) and the Fire Extent Index (FEI) for thirteen fire history sites (grey line).

### 2.3.2 Recent Climate Data

Recent climate data relies on instrumental records. The PDSI dataset used here (available from: <https://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers/overview>) from 1895-2016 gives monthly values of divisional for the PDSI for Oklahoma and Texas (Figure 19, Palmer 1965, Heddingtonhaus and Sabol 1991, Heim

2002). Here, divisional data is averaged for each state, for each month in each year in the dataset. Long-term drought is cumulative, so the intensity of drought during the current month is dependent on both the current weather patterns and the cumulative patterns in previous months.

To evaluate recent SST values, again monthly weather station data was utilized (Figure 19). Although the dataset is available from 1866-2017, this study only utilized values following 1935 because values prior to that year are considered less consistent (Ropelewski and Jones 1987, Allan et al. 1991, Können et al. 1998).

To show the geographical distribution of both mean annual precipitation and mean annual temperature in Oklahoma and Texas, the PRISM 30-year normals raster data was used (Figure 16, available from: <http://www.prism.oregonstate.edu/normals/>). This dataset is meant to display the average annual conditions over the most recent three full decades (Daly et al. 2004). The raster data showed that mean annual temperature increased from North to South, while mean annual precipitation decreased from North to South. These results guided the decisions to arrange fire history site analysis results from North to South.

## **2.4 Data Analysis**

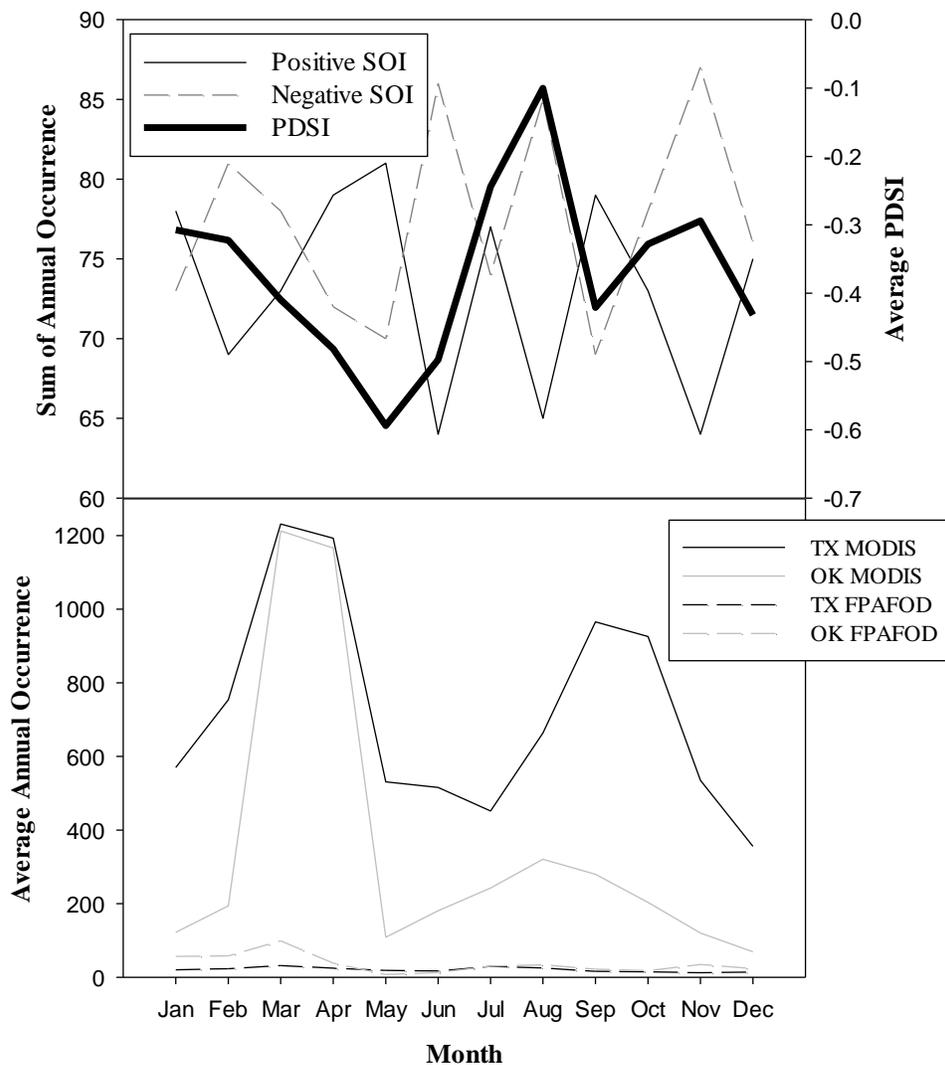
A fire extent index (FEI, Figure 18D, Guyette et al. 2002, Muzika et al. 2015) was used to evaluate the extent of fire occurrence across all sites. In this analysis, I first calculated individual site averages of percent trees scarred. From there, I determined how many sites were scarred for all calendar years in the record (0-13). Finally, I calculated the average percent of trees scarred for all sites in each individual calendar

year, using only those sites recording fire. Using this dataset, FEI was calculated from data of the number of sites scarred in a year (0 to 13, a value reflecting regional spatial extent of fire in a year) and percent of trees scarred in that year (range= 0-100, a value reflecting the scale of fire severity). The FEI is the product of the number of sites scarred and the percent of trees scarred at all the sites (Equation 1).

$$\text{FEI for year } x = (\# \text{ fire scarred sites}) (\% \text{ trees fire scarred}) \quad (1)$$

Long-term trends in fire severity were evaluated by plotting the average percentages of trees scarred at all sites in an 11-year moving average (Figure 18D). The 11-year moving average was calculated by averaging the percent sites scarred for the calendar year and the values for five years before and after the year.

To examine recent weather station data and its relationship with recent fire occurrence data, the average monthly precipitation for each month (1895-2016) was calculated and plotted against the total sum of positive and negative Southern Oscillation Index (SOI, 1935-2016) values (Figure 19). This was compared with the average monthly sums of fire occurrence from the MODIS (2001-2016) and FPAFOD (1980-2014) datasets. The spatial distribution of FPAFOD records is observed to be less widespread than that of MODIS (Figure 17), although the data covers more years.



**Figure 19.** Top: Sum of monthly positive and negative occurrences of the Southern Oscillation Index (SOI, 1935-2016, Ropelewski and Jones 1987, Allan et al. 1991, Können et al. 1998) and the monthly average values of the Palmer Drought Severity Index (PDSI, 1895-2016, Palmer 1965, Heddinghaus and Sabol 1991, Heim 2002) in Oklahoma and Texas, USA. Bottom: Average monthly fire occurrences from the Moderate Resolution Imaging Spectroradiometer Active Fire Product (MODIS, 2001-2016, Giglio et al. 2003) and the Fire Program Analysis Fire Occurrence Database (FPAFOD, 1980-2014, Short 2014) in Oklahoma and Texas, USA.

To evaluate fire occurrence and PDSI and ENSO, superposed epoch analysis (SEA) in FHAES (Brewer et al. 2011) was utilized. SEA was conducted to determine the influence of regional drought and ENSO on fire events (Fulé et al. 2005). We compared fire occurrence with climate index values during fire years, six years prior to fire years,

and four years after fire years. To assess statistical significance of the SEA results, we calculated 95%, 99% and 99.5% confidence intervals using bootstrapped distributions of climate data in 1000 trials. This analysis was conducted at individual site levels (Figure 20), and in accordance with sub-periods identified at a site-specific level (Table 7). To evaluate regional fire occurrence and PDSI and SOI in SEA, fire occurrence years in which more than one site was scarred were used. The analysis began with years in which at least two sites were scarred, then increased to years in which at least three sites were scarred, adding one additional site until the analysis included only years in which  $\geq 8$  sites were scarred, the highest number of sites scarred in any fire event (Figure 21). This analysis was done in stratified time periods before and after European-American Settlement (here defined as pre-1877 and post-1877) and stratified by geographic location from North to South. The year of 1877 was chosen to define this period as the average end of the pre-EAS period.

	Site	All Years		Pre-EAS		Post-EAS		Recent Use	
		PDSI	SOI	PDSI	SOI	PDSI	SOI	PDSI	SOI
<b>North</b>	Tall grass	-6		-3, -4					
	Key stone							n/a	n/a
	Nickel								
	Okmulgee								
	Deep Fork							n/a	n/a
	Rain Gauge						3	n/a	n/a
	Hollis Canyon	-1	-2	-1			-2	n/a	n/a
	French Lake	-1				-1		n/a	n/a
	Cache Creek			0		-5		n/a	n/a
	Tishomingo								
	Hagerman				2		1		
	Purtis Creek	-1		-1				n/a	n/a
<b>South</b>	Bastrop		-4				-4,-2		-4

**Figure 20.** Superposed Epoch Analysis (SEA) results for Palmer Drought Severity Index (PDSI, Cook et al. 2004) and Southern Oscillation Index (SOI, Cook et al. 2008) with thirteen fire history sites arranged from North to South and stratified by four time periods: a time period containing all years at the site, pre-European American Settlement, post-European American settlement, and a period of public ownership (where applicable). Blue PDSI boxes indicate that conditions were significantly wetter than expected in the lagged year contained in the box, while red boxes indicate conditions were significantly drier than expected in the lagged year contained within the box. Blue SOI boxes indicate that SOI conditions were significantly higher than expected in the lagged year contained in the box, while red boxes indicate conditions were significantly lower than expected in the lagged year contained within the box. All relationships significant at 95% confidence intervals. Blank boxes represent no significant relationship.

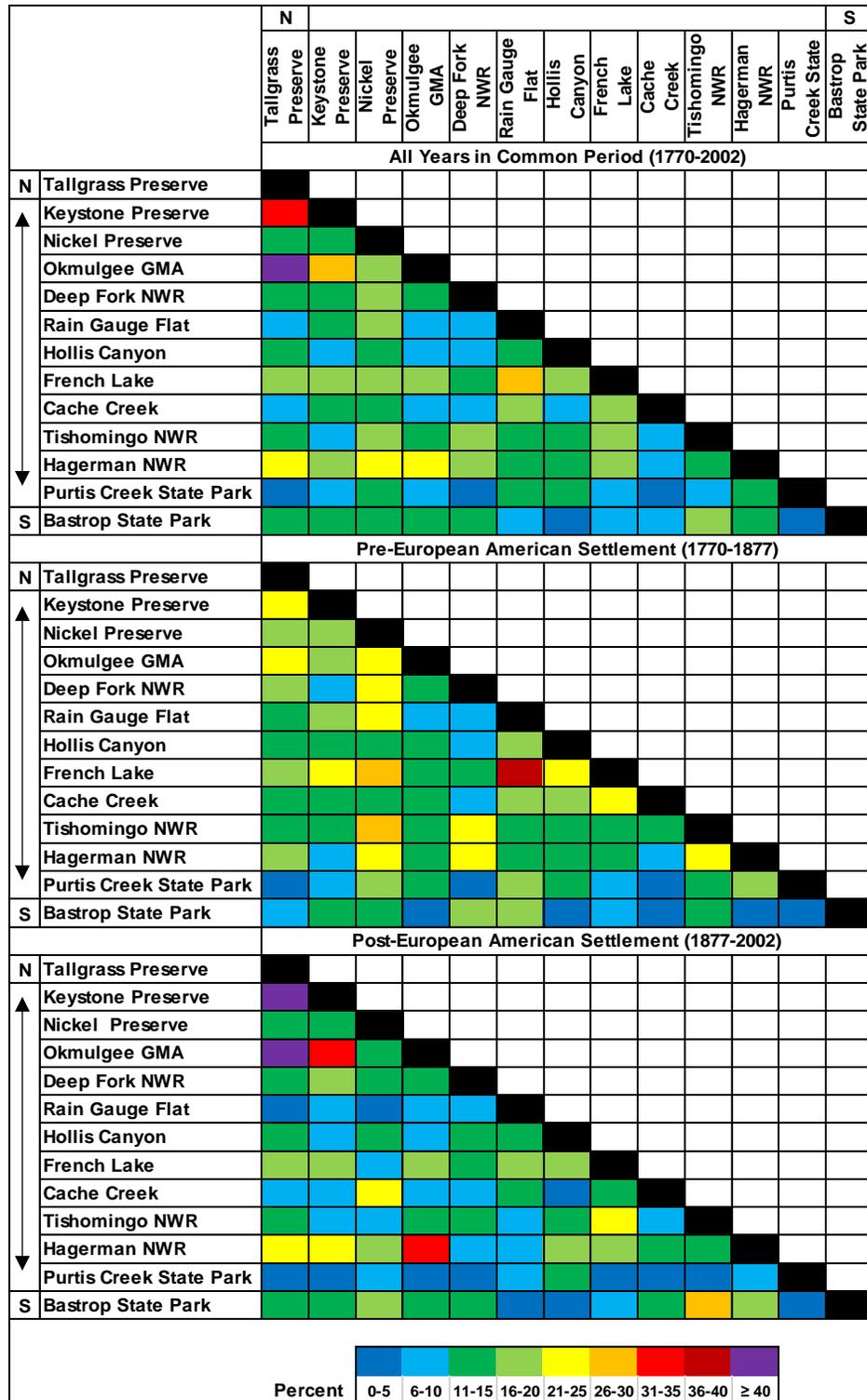
Sites Scarred	All Years			Pre-EAS			Post-EAS		
	Number of Years	PDSI	SOI	Number of Years	PDSI	SOI	Number of Years	PDSI	SOI
≥ 2	192			83			109		4
≥ 3	137			51		-6	86		
≥ 4	87	0		38	0	0,2	49		
≥ 5	47	0	-2	23	0	-5	24		1
≥ 6	20			10	0		10		0
≥ 7	8	0		4			4	0	
≥ 8	4			2	-1	-1	2	0, 1	

**Figure 21.** Superposed Epoch Analysis (SEA) results for Palmer Drought Severity Index (PDSI, Cook et al. 2004) and Southern Oscillation Index (SOI, Cook et al. 2008) values by increasing numbers of fire history sites scarred from a possible thirteen sites scarred across the Southcentral United States by three time periods: a time period containing all years in the common period (1770-2002), a pre-European American Settlement period (1770-1877), and a post-European American Settlement period (1878-2002). Blue PDSI boxes indicate that conditions were significantly wetter than expected in the lagged year contained in the box, while red boxes indicate conditions were significantly drier than expected in the lagged year contained within the box. Blue SOI boxes indicate that SOI conditions were significantly higher than expected in the lagged year contained in the box, while red boxes indicate conditions were significantly lower than expected in the lagged year contained within the box. All relationships significant at 95% confidence intervals. Blank boxes represent no significant relationship.

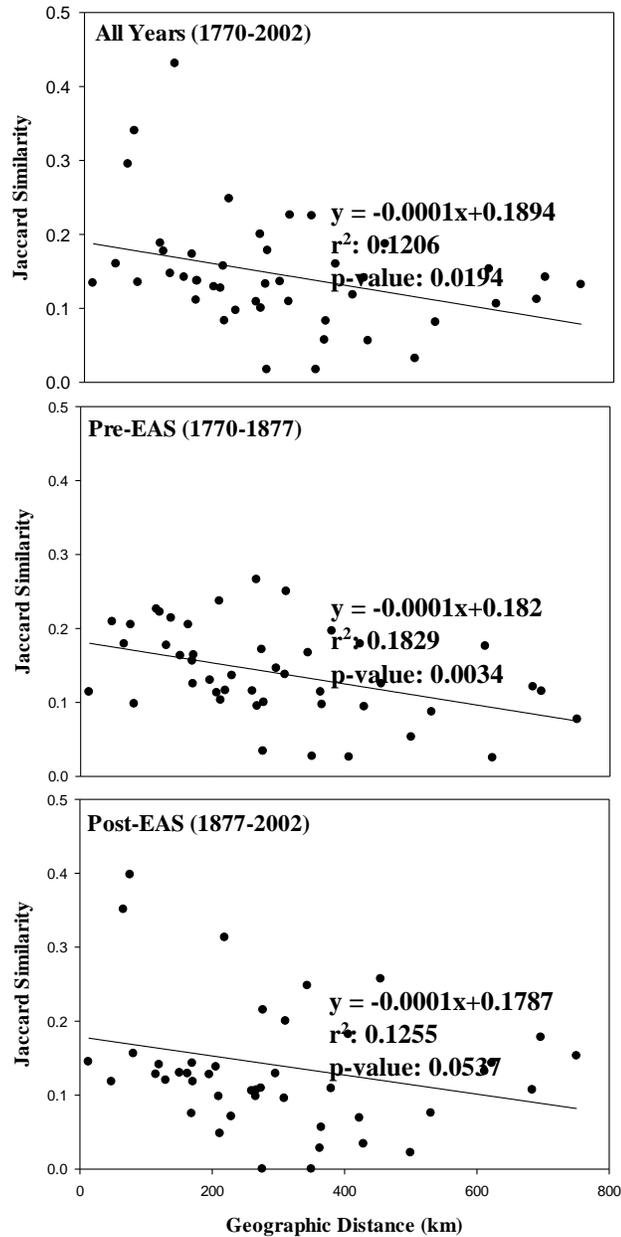
From FHAES, I used the Jaccard Index for binary comparison (Figure 22). The Jaccard Index is a calculation of the number of instances two different sites record fire in the same year (A), and expressed as a proportion of all years in which one of the sites recorded fire (B) the other site recorded fire (C) the two different sites record fire (A). We expected that the highest Jaccard similarity would be found in geographically similar sites, while the lowest would be found in the most dissimilar geographic sites. The equation used for this index is:

$$\text{Jaccard Similarity} = [A / (A+B+C)] \quad (2)$$

Values in the Jaccard Similarity Index range from 0 to 100, and are often presented as a percentage. Jaccard similarity values were computed for all site combinations, and again presented with results arranged from North to South to examine relationships between site geography. This analysis was conducted for three periods: a period containing all years in the common period among all thirteen sites (1770-2002), a Pre-EAS period (1770-1877) and a Post-EAS period (1877-2002). Scatterplots were developed of the Jaccard similarity between sites against the geographic distance between them (Figure 23). The geographic distance was computed by measuring the distance, in kilometers, between study sites in ArcGIS (ESRI 2011). One distance was computed for all sites at Wichita NWR (Cache Creek, French Lake, Hollis Canyon and Rain Gauge Flat) as they are located within close proximity. Scatterplots were developed for three time periods: a period containing all years in the common period among all thirteen sites (1770-2002), a Pre-EAS period (1770-1877) and a Post-EAS period (1877-2002). Regression lines were computed for all of the scatterplots, and the equations,  $r^2$  values, and p-values were determined for all regression lines. Results of this analysis were determined to be significant if p-values were  $<0.05$  (Figure 23).



**Figure 22.** Binary comparison matrices for thirteen fire history sites arranged by geographic location from North to South and by three time periods: a time period containing all years in the common period (1770-2002), a pre-European American Settlement period (1770-1877), and a post-European American Settlement period (1878-2002). Colors correspond to increasing Jaccard similarity values between sites progressing from low (cool) to high (hot) values (colors).



**Figure 23.** Relationship between Jaccard similarity of fire events and distance for thirteen fire history sites across the greater Cross Timbers area by three time periods: a time period containing all years in the common period (1770-2002), a pre-European American Settlement period (1770-1877), and a post-European American Settlement period (1878-2002). Points represent the Jaccard similarity between two sites. Regression lines and statistics are calculated for all data.

Pearson correlations were calculated to determine whether recent averaged monthly fire occurrence data (MODIS, 2001-2016) and average annual PDSI values per month (2001-2016) were related (Table 8). The FPAFOD dataset was omitted from this analysis because the data was not equally distributed in the region of study (Figure 17).

**Table 8.** Pearson correlations between monthly fire occurrences (MODIS, 2001-2016, Giglio et al. 2003) and PDSI values (period 2001-2016; Palmer 1965, Heddington and Sabol 1991, Heim 2002). Significant ( $p < 0.05$ ) correlations are shaded in gray.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Years	15	15	15	15	15	15	15	15	15	15	15	15
Fires (n)	10383	14221	36663	35387	9593	10444	10409	14765	18680	16940	9825	6376
r	-0.48	-0.44	-0.39	-0.47	-0.60	-0.60	-0.36	-0.32	-0.72	-0.56	-0.64	-0.68
p-value	0.07	0.10	0.15	0.08	0.02	0.02	0.19	0.24	0.00	0.03	0.01	0.01

### 3. Results

Comparisons between averaged monthly fire occurrences in both MODIS and FPAFOD show that fire occurrence is highest from March until April, and lowest in December- although this is expressed more strongly in both OK MODIS and TX MODIS than in the FPAFOD dataset (Figure 19). The PDSI is highest in August and lowest in May (Figure 19). The positive SOI has the lowest sum of annual occurrences in June, August and November and the highest sum of annual occurrences in May and September. The negative SOI observes the lowest sum of annual occurrences in May and September, and the highest sum of annual occurrences in June, August and September (Figure 19). Pearson correlations indicated that fire occurrence and PDSI are significantly correlated in six months (May, June, September, October, November, December), and not significant in six months (January, February, April, July, August, Table 8). There were no significant relationships between monthly occurrences of total positive or negative SOI values and fire occurrence in this period (Figure 19).

### **3.1 Site-Scale Superposed Epoch Analysis (SEA)**

In the SEA analysis between annual PDSI, ENSO and fire occurrence at the thirteen fire history sites (Figure 20), results were stratified for four time periods. In the period including all years, conditions were significantly drier than expected at a lag to fire events of -1 at both Hollis Canyon and French Lake. Additionally, conditions were wetter than expected six years prior and one year prior to the fire events at Tallgrass Prairie Preserve, and Purtis Creek State Park, respectively. In the same period, SOI was lower than expected 4 years prior and 2 year prior to fire events at Bastrop and Hollis Canyon, respectively.

In the Pre-EAS period, conditions were significantly drier than expected at a lag to fire events of -3 and -4 years at Tallgrass Prairie, a -1 year at Hollis Canyon, and no lag (0) at Cache Creek. Conditions were significantly wetter than expected at a -1 year lag to fire events at Purtis Creek State Park. In the same period, SOI was higher than expected 2 years after fire events at Hagerman NWR.

In the Post-EAS period, conditions were drier than expected at a -1 year lag to fire events at French Lake, and significantly wetter at a -5 year lag to fire events at Cache Creek. In the same period, SOI was lower than expected at two years after and two years prior to fire events at Rain Gauge Flat and Hollis Canyon, respectively. SOI was higher than expected one year after, and both 4 and 2 years before fire events at Bastrop State Park. In the Recent Use period, the SOI was higher than expected four years prior to fire

events at Bastrop State Park, and no other conditions were significantly different than expected at any other site included in the analysis for this time period.

Overall, the most frequently occurring fire-drought relationship was observed during a lag of 1 year prior to fire events. Further, more instances where the SOI was lower than expected and conditions were drier than expected were observed than instances in which the SOI was higher than expected and conditions were wetter than expected. There were also more departures from expected results found between PDSI and fire occurrence than with SOI and fire occurrence. The time periods with the most departures from expected results were the All Years and post-EAS periods, while the fewest occurred in the Recent Use Period. No departures from expected results were observed at the Keystone Ancient Forest Preserve, Nickel Family Nature and Wildlife Preserve, Okmulgee Game Management Area, Deep Fork NWR or Tishomingo NWR at any time period.

### **3.2. Regional-Scale Superposed Epoch Analysis (SEA)**

In the regional fire SEA analysis (Figure 21), results were stratified by three time periods: a period including all years in the common period between all thirteen fire history sites (1770-2002), a Pre-EAS period (1770-1877) and a post-EAS period (1877-2002). In years in which at least two sites were recording fire, SOI was higher than expected four years after fire events in the Post-EAS period. In years in which at least three sites were recording fire, the SOI was significantly higher than expected six years prior to fire events in the Pre-EAS period. In years in which at least four sites were recording fire, conditions were significantly drier than expected at no lag (0 years) to fire

events in both the All Years and Pre-EAS period. The SOI was significantly lower than expected at a 0 year lag and in 2 years following fire events in the Pre-EAS period. In years in which at least five sites were recording fire, conditions were drier than expected at no lag (0 years) to fire events in the All Years and the pre-EAS period. The SOI was higher than expected 2 years prior to fire events in the All Years and Post-EAS period, respectively. The SOI was significantly lower than expected five years prior to fire events in the Pre-EAS period. In years in which at least six sites were recording fire, conditions were significantly drier than expected at no lag (0 years) to fire events in the Pre-EAS period. Additionally, the SOI was significantly higher than expected in the year of fire events in the Post-EAS period. In years in which at least seven sites were recording fire, conditions were significantly drier than expected in the year of fire events in both the All Years and the Post-EAS period. In years in which at least eight sites were recording fire, conditions were wetter than expected one year prior to fire events in the Pre-EAS period, and significantly drier in the year of and one year prior to fire events in the Post-EAS period. In the Pre-EAS period, the SOI was also significantly higher than expected one year prior to fire events. There were more instances where conditions were drier than expected or where the SOI was significantly higher than expected than instances where conditions were wetter than expected or where the SOI was significantly lower than expected. The most common departures from expected results were conditions were drier than expected in the year of the fire occurrence (0 year lag). Most departures from expected results were observed in the Pre-EAS period, and in years in which at least five sites were recording fire.

### 3.3 Jaccard Similarity Index Analysis

In the binary comparison matrices analysis (Figure 22), results were stratified by three time periods: a period including all years in the common period between all thirteen fire history sites (1770-2002), a Pre-EAS period (1770-1877) and a post-EAS period (1877-2002). In the All Years Period, the Jaccard similarity values had an average of 14% for all sites, and ranged from 2-43%, with the highest similarity between Tallgrass Prairie Preserve and Okmulgee Game Management Area (43%). The lowest similarity in this period was 2% between Purtis Creek State Park and Deep Fork NWR, between Purtis Creek State Park and Cache Creek, and between Bastrop State Park and Purtis Creek State Park. The sites with the highest average similarity were Tallgrass Prairie Preserve, Okmulgee GMA, French Lake, and Nickel Family Nature and Wildlife Preserve with 17% similarity. The lowest was Purtis Creek State Park with 7% similarity.

In the Pre-EAS period, the Jaccard similarity values had an average of 14% for all sites and ranged from 3-36%, with the highest similarity between French Lake and Rain Gauge Flat (36%). The lowest similarity in this period was 3% between Bastrop State Park and Okmulgee GMA, between Bastrop State Park and Hollis Canyon, between Bastrop State Park and Cache Creek, between Bastrop State Park and Purtis Creek State Park and between Deep Fork NWR and Purtis Creek State Park. The site with the highest similarity was Nickel Family Nature and Wildlife Preserve with 20% while the site with the lowest similarity was Bastrop State Park with 9%.

In the Post-EAS period, the Jaccard similarity values had an average of 13% and ranged from 0-52%, with the highest similarity between Tallgrass Prairie Preserve and Okmulgee Game Management Area (52%). The lowest similarity in this period was between Deep Fork NWR and Purtis Creek State Park, between Cache Creek and Purtis Creek State Park, and between Bastrop State Park and Purtis Creek State Park. In all time periods, the most common similarity values between sites were between 11-15% similar. No trends were observed at the North to South gradient of sites in this analysis. The sites with the highest similarity were Tallgrass Prairie Preserve and Bastrop State Park with 18%, while the site with the lowest similarity to other sites was Purtis Creek State Park with 4%.

In the analysis to evaluate the relationship between Jaccard similarity and geographic distance (Figure 23), results were stratified by three time periods: a period including all years in the common period between all thirteen fire history sites (1770-2002), a Pre-EAS period (1770-1877) and a post-EAS period (1877-2002). Significant ( $p < 0.05$ ) relationships were found between Jaccard similarity and geographic distance in the All Years and the Pre-EAS period, but not in the Post-EAS period. In the All Years period, the equation for the regression line for the data was  $y = -0.0001x + 0.1894$  ( $r^2 = 0.12$ ,  $p = 0.02$ ). In the pre-EAS period, the equation for the regression line for the data was  $y = -0.0001x + 0.182$  ( $r^2 = 0.18$ ,  $p = 0.03$ ). In the post-EAS period, the equation for the regression line for the data was  $y = -0.0001x + 0.1787$  ( $r^2 = 0.1255$ ,  $p = 0.0537$ , Figure 23).

#### **4. Discussion**

Historically, there is a strong relationship between drought and regional-scale fire synchrony across the greater Cross Timbers ecoregion. This relationship is particularly strong in the pre-fire suppression period in this region, before EAS. The influence of climatic factors can be observed over time, and across large geographic regions, with high percentages of fire years displaying synchrony between at least two study sites (87%) in the period of analysis (1770-2002). Across the region of study, variations in local land-use history likely altered the strength of the relationship between fire occurrence and climate, observed through temporal changes in fire regimes across the greater Cross Timbers ecoregion. The findings in the greater Cross Timbers region are similar to findings in other regions of the U.S., and have implications in wildfire management in the future.

#### **4.1 Site-Scale Findings**

The relationship between fire occurrence and drought was largely unclear at the site scale in the greater Cross Timbers region. No persistent relationship with PDSI or with SOI was observed between sites or across time-periods. Allen et al. (2011) showed a lack of relationship between fire and drought in the reconstruction of fire occurrence at Tallgrass Prairie Preserve, which was attributed here to the high frequency of fire at the site. In contrast, the four sites at the Wichita NWR showed conditions were significantly drier than expected in the year of fire events, or during the preceding 2 years (i.e. at a lag of -1 or -2). Sites at Wichita NWR differed in their fire and drought relationships depending on the time period considered (Stambaugh et al. 2014). In this research, we added three additional sites to a robust collection of fire history sites in the greater Cross

Timbers region in order to better evaluate trends in this fire-drought relationship. With the addition of these data, we observed no significant relationship between fire occurrences and either PDSI or ENSO although the majority of relationships observed at this scale showed drier than expected conditions (negative PDSI or positive SOI) at a lag with fire occurrence (Figure 20). This result indicates that fire occurrence may be reliant on low moisture conditions in times of drought. The lack of clarity in drought results at the site scale likely stems from site-specific fire influences that overwhelm climatic influences, or mask them in some way.

#### **4.2 Regional Scale Findings**

When examining fire-climate relationships at the regional scale, we observed that drought was a significant driver of the synchrony in fire occurrence in the greater Cross Timbers ecoregion. Drier than expected conditions were observed in the year of fire events at the regional level (both  $\geq 4$  and  $\geq 5$  sites recording fire). This relationship was less apparent in the post-EAS period, when, presumably, human influences overwhelmed the climate signal. In the post-EAS period, only fire years with at least 7 or at least 8 sites recording fire had significantly drier than expected conditions in the year of the fire. These years (1895, 1925, 1940, and 1953) recorded some of the most severe droughts in the post-EAS period, with 1925 and 1953 recording PDSIs below -4.0, and being the most severe droughts of this period in the greater Cross Timbers region. The relationship between drought and current year fire activity suggests that a single year of drought is the only necessary condition for regionally-synchronous fire activity, where drought increases the probability of ignition. It should be noted that not all regional droughts had

regional synchrony with fire occurrence, and not all synchronous fires coincided with negative PDSI conditions. This suggests that fire occurrence is also limited by some local control or factor (i.e. ignition events).

While widespread burning in low moisture conditions was observed in the greater Cross Timbers region, no apparent lag with years with high moisture availability was observed. This indicates that fire occurrence in this region is dependent on drought, and not dependent on an increase in production of fine fuels in previous years- a relationship that has been suggested in other regions (Swetnam and Baisan 1996, Swetnam and Betancourt 1998, Westerling et al. 2003). This antecedent pattern of fine-fuel growth production has been interpreted as a buildup of surface fuels (grasses and forbs) during exceptionally wet years, which then burn more extensively and readily during subsequent drought years (Swetnam and Baisan 1996, Swetnam and Betancourt 1998, Westerling et al. 2003). During a fire year, drought conditions dry the vegetation- creating enhanced fire ignition conditions (Brown 2006). Drought and subsequent drying and accumulation of fuels following wet years creates the potential for large-scale fires in the southwestern U.S. (Swetnam 1990, Collins et al. 2006).

No clear relationship between ENSO and fire occurrence was observed. This result is in contrast with other regional studies, where the ENSO-fire relationship with synchronous regional fire was more closely observed. For example, Yocum et al. (2017) observed that La Niña conditions were positively associated with regionally synchronous fire years in northern Mexico. ENSO has been identified as a strong control in fire extent in the southwestern U.S. (Swetnam and Betancourt 1990) and in the Pacific Northwest (Heyerdahl et al. 2002). In these regions, synchronous fire was associated with the drier

and warmer conditions of the ENSO phase. In California, ENSO was not a strong control of fire extent at the regional scale, although a weak relationship was found at some of the sites in the study region (Taylor et al. 2008).

Based on fire occurrence over the last 2 decades, most fires occurred in the months of March and April. No clear relationship with PDSI was found in those months (Figure 9). Rather, fire in the months following this peak in fire activity (i.e. May and June) were significantly correlated with PDSI, as were September-December. These results suggest that the regional fire activity in peak fire season (2001-2016) is not related to PDSI conditions, but rather related to anthropogenic factors.

#### **4.3 Fire Similarity Among Sites**

Jaccard similarity was significantly related to geographic distance between sites. This relationship was not apparent in the post-EAS period from 1877-2002. In the All Years (1770-2002) and the Pre-EAS (1770-1877) periods, fire dates were more similar at closer geographic regions. The disparity in results between the pre-EAS and post-EAS periods may be due to fuel fragmentation or disruption in the years in the post-EAS period (1877-2002). It is also possible that in the post-EAS period, humans constrained the fire-climate relationship, and affected the fire/ drought relationship. While shared fire years were observed at great geographic distances (>0% Jaccard similarity between sites up to 700 km), the synchrony of fires appears significantly stronger at shorter geographic distances. Yocum et al. (2017) observed that at 67 sites in northern Mexico, there were no effects of land-use change on fire occurrence before 1900. This contrasts with the results in the greater Cross Timbers region where landscape disruption due to the migration and

removal of Native Americans, grazing, and other land use changes (including fire suppression) was observed earlier. Across the greater Cross Timbers region, we observed disruption in the relationship between drought and fire occurrence and between fire history site similarity and distance between the pre-EAS and post-EAS periods. We used 1877 to delineate the pre-EAS period from the post-EAS period, when EAS had altered fire history sites in some way. Disruption of trends in fire-climate relationships and in shared fire event date trends in the post-EAS period brings increased attention to the magnitude of land-use changes in the greater Cross Timbers region in the mid-to-late 1800s and its ecological impact. This effect may also be an explanation for the lack of a relationships between months with the highest number of fires and PDSI in recent decades. In the Ozarks, Guyette et al. (2002) describes this “fuel fragmentation” stage as a time of “artificial fuel breaks caused by livestock grazing, road building, and the conversion of field to forest to crop land and pasture.” This stage coincided with increased human population densities due to improved systems of trade and human movement such as railroads and markets. This pattern of regional disruption of fuels is certainly plausible in the Cross Timbers region, and appears to be evident in the fire-occurrence record of the region. Human impacts on fires in this region since EAS are well documented and have resulted from altered ignition patterns associated with land and debris clearance, fire suppression, and fire exclusion through a number of methods.

Results in the greater Cross Timbers region are comparable to results observed elsewhere in the U.S. Marlon et al. (2012) found that both temperature and drought predicted biomass burning through the late 1800s in the Western U.S., but that the relationship dissipated following this period, where human activities and the ecological

effects of recent severe fire activities caused a large, abrupt decline in burning. Taylor et al. (2016) observed a similar relationship in California, where the strong multi-decadal relationship between drought and fire decayed, and then disappeared following fire suppression. Elsewhere in the country, there was a strong relationship between drought and regional-scale fire synchrony in the pre-fire suppression period in forests of the southwestern U.S. (Swetnam and Baisan 2003), in the Pacific Northwest (Heyerdahl et al. 2001), and in the mountains of the West (Donnegan et al. 2001).

Findings here suggest that anthropogenic ignitions have driven the fire regime across the greater Cross Timbers region from the post-EAS period to the present-day. Fire occurrence across the region in the last two decades appears to be unrelated to drought or ENSO, with the exception of extreme drought events, and rather driven by anthropogenic influence. As the role of climate and humans is further defined in the region, models and management efforts will be adapted to mitigate the occurrence of wildfires across the region. This study has identified the drivers of fire occurrence over the last three centuries, and added to the national knowledge of the role of drought and humans in the occurrence of fire.

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