TORNADO DAMAGE AND FIRE HISTORY IN THE CROSS TIMBERS OF THE TALLGRASS PRAIRIE PRESERVE, OKLAHOMA

By

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PREFACE

My thesis is composed of 3 chapters. Chapter one is a general introduction to the Cross Timbers. Chapter Two entitled "Tornado Damage of *Quercus stellata* and *Quercus marilandica* in the Cross Timbers, Oklahoma, USA" is a manuscript accepted by *Journal of Vegetation Science* on February 2006. Chapter Three is "Fire History and seasonality of fire events in the Cross Timbers, Oklahoma". I formatted Chapter Two using following the guidelines of the journal.

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CHAPTER ONE

Introduction – Cross Timbers

The Cross Timbers are a mosaic of grassland, savanna, and upland forest occurring at the transition between the eastern deciduous forests and the grasslands of southern Great Plains (Francaviglia 2000). The Cross Timbers stretch from southeastern Kansas through Oklahoma and into central Texas (Küchler 1964; Therrell & Stahle 1998; Hoagland et al. 1999; Hoagland 2000) (Fig.1) and approximately half (2.5 million ha) of the Cross Timbers are in Oklahoma (Küchler 1964). During periods of climatic amelioration, oak species increased in abundance and the Cross Timbers established (Hoagland *et al*. 1999). The name "Cross Timbers" probably came from early explorers, who traveled across the Cross Timbers, and "crossed alternating patches of forests and prairies and so affixed to these forests the name 'Cross Timbers'" (Mattoon & Webster 1943).

In the Cross Timbers, two tree species, *Quercus marilandica* and *Q. stellata*, dominate the overstory (Abrams 1992; 2005; Clark *et al*. 2005). The short and stout stems of these two species combined with the rocky nutrient-poor soil of the Cross Timbers region prevented their commercial logging or removal so that the land could be cultivated (Therrell & Stahle 1999; Hoagland *et al.* 1999; Hoagland 2000). Therefore, relatively undisturbed tracts ancient Cross Timbers, containing thousands of 200 – 400 year old *Quercus stellata*, remain in Oklahoma (Stahle 1996; Therrell & Stahle 1998;

Clark 2003; Clark *et al*. 2005). The Cross Timbers is not only the largest ecosystem in southcentral North America, but also may contain one of the least anthropogenically disturbed forests in eastern North America (Stahle 1996; Therrell & Stahle 1998).

Natural disturbances, such as windstorms (Forman 1947; Oliver & Larson1990; Peterson 2000) and fire (Dyksterhuis 1948; Irving 1956; Smith 1996; Pyne 1997; Hoagland *et al*.; 1999, Clark; 2003) have played an important role in the Cross Timbers. They impact the Cross Timbers dynamics and alter species composition and abundance (Foreman 1947; Dyksterhuis 1948; Irving, 1956; Anderson 1990; Johnson *et al*. 1990; Abram 1992; Oliver & Larson1990; Engle & Stritzke 1995; Engle *et al*. 1996; Smith 1996; Pyne 1997; Hoagland *et al*. 1999; Peterson 2000; Clark; 2003; Clark *et al*. 2005).

Damage by wind disturbance may be species-specific (Everham & Brokaw 1996; Peterson 2000). Furthermore, windstorms may be critical for the persistence of some species (Batista & Platt 2003). Windstorm damage has been well studied in various regions, including central North America (e.g. Peterson & Rebertus 1997). However, windstorm effects have not been studied in the Cross Timbers (Johnson & Risser 1972; Hoagland *et al*. 1999), despite frequent tornados in the region (Oliver & Larson 1993; Peterson 2000).

Fire disturbances favor oak-dominated forests (Abrams 1992; 2005; Rouse 1986; Dey *et al*. 2004; Dey & Hartman 2005; Signell et al. 2005; Soucy *et al*. 2005). Repeated fire, both natural and anthropogenic, throughout the history of the Cross Timbers is purported to maintain the characteristic patchiness of the Cross Timbers (Forman 1947; Irving, 1956; Smith 1996; Pyne 1997; Hoagland et al. 1999; Clark 2003; Clark *et al*. 2005). Seasonality of fire events and fire return interval also affect species composition and oak forest dynamics (Engle & Stritzke 1995; Engle et al.1996; Dey & Hartman 2005; Abrams 1992). Fire, natural and/ or anthropogenic, has repeatedly appeared in the Cross Timbers (Irving, 1956; Smith 1996; Pyne 1997; Hoagland; 1999; Clark 2003), however, we know few details about fire history in the Cross Timbers.

In the oak-dominated forests of Eastern North America with the exception of the Cross Timbers, shade-intolerant oak species have been replaced by shade-tolerant species since the fire suppression era of the 1900s (Abrams 1992; 2005; Abrams *et al*. 1995; Olson 1996; Orwig *et al*. 2001; Shumway 2001; Dey 2002; Signell 2005; Soucy *et al*. 2005). In addition to fire, windstorm is important disturbance to affect structure of oak-dominated forests (Oliver & Larson 1993; Peterson 2000). Dey (2002) reviewed effects of windstorms and fires on oak-dominated forests and concluded. Windstorms presumably decrease density of forest by removing overstory trees and may promote succession to shade-tolerant or pioneer species. However, fires suppress those competitors of oak species and a combination of windstorm and fire may promote oak regeneration. Infrequent catastrophic windstorm combined with fire might affect regeneration of dominant oak species in the Cross Timbers. Knowing the historic fire regime in the Cross Timbers will help us to understand the role of disturbances in the ecology of this unique large ecosystem and allow us to compare it to other oak-dominated forests.

Other temperate forests (e.g. *Fagus-Acer* forests, *Pinus-Juniperus* woodlands), like the Cross Timbers, have two codominant species. Therefore, understanding the effects of disturbance on the Cross Timbers has broader relevance for coexistence theory.

The research described in this thesis was performed in the Tallgrass Prairie Preserve, Osage County, Oklahoma. It has managed by the Nature Conservancy since 1990 and no documentation of fire history in the study area is available before 1993. The objectives of the research presented in this thesis were 1) to examine how a severe tornado in 2003 affected the two dominant trees species, *Quercus marilandica* and *Q. stellata*, of the Cross Timbers with respect to damage and mortality and how such patterns varied as a function of tree size, 2) to reconstruct a fire chronology and examine seasonality of fire events and fire return interval using disks from trees killed by the 2003 tornado, and 3) to examine how reliably *Q. marilandica* and *Q. stellata* record post-1993 fire events.

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Fig. 1

Fig. 1. Location of the Cross Timbers according to Küchler (1964).

CHAPTER TWO

Tornado Damage of *Quercus stellata* and *Quercus marilandica* in the Cross Timbers,

OKLAHOMA, USA

Abstract

Questions: The Cross Timbers are a mosaic of savannas, grasslands and upland forests, occupying a significant portion of southcentral North America. Our questions here were (i) how does a severe tornado affect the two most dominant tree species (*Quercus marilandica* and *Q. stellata*) of the Cross Timbers with respect to damage and mortality, and (ii) how do such patterns vary as a function of tree size? What are the implications of disturbance for codominance in species-poor systems?

Location: The Cross Timbers in Oklahoma, USA.

Methods: We established a 14.48-ha permanent plot following a severe tornado in 2003. We identified, numbered and tagged each tree and recorded its diameter at breast height (DBH), spatial coordinates, status (dead or alive), and damage type. We examined (1) relative abundance before and after the tornado, (2) differences in damage and mortality, and (3) the influence of tree diameter on the probability of damage and mortality for each species.

Results: Differences in species identity and tree characteristics, significantly affected tree mortality by the tornado, after accounting for spatial locations. The odds of mortality were 12.0 times greater for *Q. marilandica* than for *Q. stellata*. Such greater vulnerability of *Q. marilandica* versus *Q. stellata* was also reflected in changes in density and basal area. Tree diameter clearly influenced the damage and mortality pattern in *Q. stellata*; larger trees sustained more damage and mortality. However, *Q. marilandica* did not exhibit size-dependent mortality.

Conclusion: The tornado affected the two dominant species differently. The intra- and inter-specific differences in windstorm susceptibility may allow coexistence of the two species and are potentially important in the dynamics of the Cross Timbers. Species more damaged might finally benefit from the wind disturbance due to their resprouting ability.

Key words: coexistence, Cross Timbers, disturbance*, Quercus marilandica, Quercus stellata,* logistic regression, tornado, windstorm

Nomenclature: Kartesz (1999).

Abbreviations: TGPP = Tallgrass Prairie Preserve.

Introduction

Catastrophic windstorm is an important disturbance that impacts forest structure and dynamics (Webb 1989; Greenberg & McNab 1998; Peterson 2000a; Batista & Platt 2003). Wind disturbance alters species composition (Zimmerman et al. 1994; Liu et al. 1997; Peterson & Rebertus 1997; Peterson 2000b), and successional (Putz 1983; Abrams & Scott 1989; Arévalo et al. 2000). Furthermore, windstorm may be critical for some species' persistence (Batista & Platt 2003).

Forest damage and subsequent response are contingent upon factors such as topography, canopy structure, and wind intensity (Everham & Brokaw 1996; Peterson 2000a). Damage may be species-specific (Everham & Brokaw 1996; Peterson 2000a). Susceptibility to wind is generally higher in pioneer/early-successional species compared to nonpioneer/late-successional species (Webb 1989; Foster & Boose 1992; Zimmerman et al. 1994; Dyer & Baird 1997). Tree size also determines risk of damage or mortality: vulnerability generally increases with increasing stem diameter (Zimmerman et al. 1994; Arévalo et al. 2000; Peterson 2000a; Canham et al 2001), although some studies report high vulnerability at intermediate (Dyer & Baird 1997; Zimmerman et al. 1994; Wolf et al. 2004) or smaller diameters (Milton et al. 1994; Arévalo et al. 2000). Some species do not exhibit size-dependent mortality (Dyer & Baird 1997, Greenberg & McNab 1998).

The Cross Timbers are a mosaic of savanna, grasslands, and upland forests dominated by *Quercus marilandica* and *Q. stellata*, occurring at the transition between the eastern deciduous forests and the grasslands of the southern Great Plains

(Francaviglia 2000). They stretch from southeastern Kansas through Oklahoma and into central Texas (Küchler 1964; Therrell & Stahle 1998). Although the Cross Timbers occupy much of the southcentral United States, we know little about their dynamics. Like other temperate forests (e.g. *Fagus-Acer* forests, *Pinus-Juniperus* woodlands) they have two codominant species. Therefore, understanding the effects of disturbance on Cross Timbers has broader relevance for coexistence theory.

Windstorm damage has been well studied in various regions, including central North America (e.g. Peterson & Rebertus 1997). However, windstorm effects have not been studied in the Cross Timbers (Johnson & Risser 1972; Hoagland et al. 1999), despite frequent tornados (Oliver & Larson 1993; Peterson 2000a). Studies of wind disturbance in the Cross Timbers will allow us to compare it with better-known systems, and thereby help us better understand the role of disturbance in forest dynamics.

In this paper, we document the immediate effects of a 2003 tornado on the two most dominant species of a Cross Timbers stand, *Q. marilandica* and *Q. stellata*. Although both species have similar ecological characteristics, *Q. marilandica* (section *Lobatate,* red oak group) has slightly more pioneer/early-successional tendencies compared to *Q. stellata* (section *Quercus*, white oak group) (Iverson et al. 1999). Higher vulnerability of the red oak versus white oak group to wind disturbance was reported in other systems (Greenberg & McNab 1998; Dyer & Baird 1997). We examine whether (i) damage and mortality differ between the two species and (ii) tree size (diameter) affects damage and mortality within each species. We interpret our results in relation to the potential importance of wind disturbance in the dynamics of the Cross Timbers.

Methods

Study area

The 15 783-ha Tallgrass Prairie Preserve (TGPP) (between 36.73° and 36.90°N latitude; 96.32° and 96.49°W longitude, elevation 253m-366m) is managed by The Nature Conservancy and located in Osage County in north-central Oklahoma (Hamilton 1996). Approximately 90% of the TGPP is composed of grasslands and the remaining is primarily forest. Most of the forest is the Cross Timbers dominated by *Q. stellata* and *Q. marilandica* (Palmer et al. 2003). Mean annual winter and summer temperatures are 3.9°C and 26°C, respectively (Anon. 2003a). Cattle and bison graze the area. The Nature Conservancy prescribes randomized fire to maintain the grassland (Hamilton 1996). However, the tornado study site has not been burned since 2002 and is currently grazed by cattle.

On 8 May 2003, a tornado struck part of the TGPP and severely damaged the Cross Timbers located on the western edge of the TGPP. The intensity of the tornado was rated F3 (254-332km hr^{-1}, “severe”) on the Fujita Tornado Intensity Scale, which varies from F1 to F5 based on apparent damage (Fujita 1981). A tornado is short-lived phenomenon of a high-speed vertical vortex of wind; its damage is confined to the immediate vicinity of touch down (Glitzenstein & Harcombe 1988; Peterson 2000; Pryor & Kurzhal 1997). The tornado, therefore, creates a discrete “damage” area, as with the 2003 tornado (Fig.1).

Field methods

We established a 14.48-ha permanent plot in August 2003, about three months after the tornado. It comprised areas where we found damaged trees, areas which were completely unaffected by the tornado, and patches of included grassland. We divided the plot into 1448 10m ×10m modules. The plot contains 681 grassland modules (no trees present) and 611 forest modules (at least one tree present). One hundred fifty-six modules were not analyzed because damaged trees were bulldozed to allow vehicular access.

In each module except these anthropogenically disturbed areas, we identified, numbered and tagged each tree > 2.5 cm DBH and recorded its diameter at breast height (DBH), spatial coordinates, status (dead or alive), and damage type. When a tree had more than two stems originating below 1.4 m, we tagged each stem. The damage types include snapped, snapped but still connected, standing dead, uprooted, tipup, and canopy damage. We recorded the height of the snap, if any. We classified stems with less than 70% loss of canopy branches as “moderately damaged”; those with more than 70% as “severely damaged”; and those with no living tissue above 1.4m as “dead”.

Of the 18 tree species encountered (*Carya illinoinensis, C. texana, Celtis occidentalis, Cercis canadensis, Cornus drummondii, Crataegus crus-galli, Diospyros virginiana, Fraxinus pennsylvanica, Prunus mexicana, P. serotina, Quercus marilandica, Q. shumardii, Q. stellata, Sapindus saponaria, Sideroxylon lanuginosum, Ulmus rubra, Viburnum rufidulum*), only *Quercus stellata* and *Q. marilandica* were present in sufficient numbers to permit detailed analyses of mortality and damage (Table1).

Data analysis

Since tornados (relative to other wind disturbances) have spatially discrete effects, we performed a preliminary multiple logistic regression (Hosmer & Lemeshow 2000) including spatial terms. This allowed us to examine species and diameter effects above and beyond the spatial effect. Explanatory variables included spatial coordinates and up to third-order polynomial terms plus their interactions, tree species, DBH, DBH^2, and species by DBH interaction. Since this logistic model indicated a strong spatial effect (as expected), we excluded undamaged forest from subsequent analysis (Table 2). In particular, we restricted analysis to the "damaged" area, defined as where the predicted mortality, independent of species, exceeded 20%, as assessed by the regression. This yielded 246 damaged modules (Fig.1). We tested the null hypothesis that the tornado damaged equally *Q. marilandica* and *Q. stellata* for "damaged" (i.e., moderately and severely damaged) versus "undamaged" and "dead" versus "live" (i.e., severely and moderately damaged, and undamaged) (Sokal & Rohlf 1995). We performed logistic regressions (Hosmer & Lemeshow 2000) to evaluate the effects of size on the probability of damage and mortality of each species, using DBH and its quadratic term as explanatory variables. We performed all analyses in SPSS 13.0 for Windows (Anon. 2003b) and used $p<0.05$ as a rejection criterion.

Results

There were initially ca. 1.5 times as many *Q. marilandica* stems than *Q. stellata* stems in the 246 modules. After the tornado, the proportion of these two species was reversed (Table 3). *Q. marilandica* showed high mortality and severe damage for all stem diameters. A significantly greater proportion of *Q. marilandica* was damaged or killed by the tornado than *Q. stellata* (Fig.1, 2, Table 3). Chi-squared tests were significant for “damaged” ($\chi^2 = 227.6$, $p < 0.001$) and “dead” ($\chi^2 = 338.6$, $p < 0.001$). The odds of “damaged” versus “undamaged” and “dead” versus “live” were, 8 and 12 times greater, respectively, for *Q. marilandica* than for *Q. stellata*. These interspecific differences were reflected in the change in basal area caused by the tornado. *Q. stellata* lost 14.9 % of its basal area, whereas *Q. marilandica* lost 53.0% (Table 3). Basal area of *Q. marilandica* was 1.5 times as much as that of *Q. stellata* before the tornado; the basal area of the two species became almost identical after the tornado.

The different susceptibilities of the two species are also revealed by logistic regression (Fig. 3). The probability of “moderate damaged” and “severely damaged” in both two species increased as a function of diameter ($p < 0.001$). Mortality increased significantly for *Q. stellata* ($p < 0.001$) but not for *Q. marilandica* ($p = 0.280$).

Discussion

The tornado affected *Quercus marilandica* dramatically more than *Q. stellata*.

The spatial distribution of trees relative to the storm path did not appear to contribute to the relative vulnerability of the two species. Although locally clumped, *Q. marilandica* and *Q. stellata* occur intermixed and relatively homogeneously within the study area. Thus, individuals of both species must have experienced similar wind forces, and the observed damage is likely due to tree characteristics.

The relative susceptibility of *Q. marilandica* and *Q. stellata* to windstorm we found, agree with other studies. The red oaks (*Quercus* section *Lobatae*), which includes *Q. marilandica*, are generally more vulnerable to wind damage than white oaks (*Quercus* section *Quercus*), which includes *Q. stellata*. Greenberg & McNab (1998) observed that a greater proportion of red oak species (*Quercus coccinea*, *Q. rubra* and *Q. velutina*) were uprooted by hurricane winds in the mountains of North Carolina, USA than white oaks (*Q. alba*, *Q. falcata* and *Q. prinus*). Dyer and Baird (1997) also found that *Q. rubra* (section *Lobatae*) was more susceptible to windthrow than *Q. macrocarpa* (section *Quercus*) in the prairie-forest ecotone of Minnesota, USA.

In general, pioneer/early-successional species are more susceptible to wind disturbance than nonpioneer/late-successional species (Webb 1989; Foster & Boose 1992; Zimmerman et al. 1994; Dyer & Baird 1997; Arévalo et al. 2000). This may be caused by lower wood strength of pioneers (Zimmerman et al. 1994). The red oak group exhibits pioneer-like traits. Some evidence suggests that species in the red oak group are less shade tolerant (Steele et al. 2001), are better dispersers (Abrams 2003; Steele et al. 2001), grow faster (Whitney 1994; Kauffman 2002), and are shorter-lived (Miller & Lamb 1984; Stein et al. 2003) than species in white oak group. *Q. marilandica* seems to be less shade-tolerant than *Q. stellata* and appear at sites prior to *Q. stellata* (Iverson et al. 1999; Arévalo 2002). *Q. marilandica* is short-lived whereas *Q. stellata* is long-lived (Stein et al. 2003).

Our result on size effect is consistent with studies of other red oak and white oak species. We found that the effect of tree size on mortality was less pronounced in *Q. marilandica* than in *Q. stellata*. Greenberg & McNab (1998) documented presence of size effect in *Q. alba* (section *Quercus*) and absence in *Q. rubra* (section *Lobatae*).

Interspecific differences in susceptibility to wind disturbances, as evident in our study, may have influence community composition and structure (Foster & Boose 1992; Putz & Sharitz 1991) through the removal of species with specific traits (Batista & Platt 2003). Acceleration of succession following windstorm has been suggested elsewhere (Arévalo et al. 2000; Rebertus and Meier 2001). In our study, the tornado disproportionately removed the shade-intolerant, short-lived *Q. marilandica*, and thus increased the relative abundance of the shade- tolerant, long-lived *Q. stellata*. Therefore, our study on the *immediate* effect of the tornado suggests accelerated succession. Three observations seem to conflict: 1) Throughout their geographic ranges, *Q. stellata* and *Q. marilandica* are almost invariably found together; 2) Without disturbance, *Q. stellata* may become more dominant by replacing the shorter-lived *Q. marilandica* (Kroh & Nisbet 1983); 3) Our study shows that even with disturbance, *Q. stellata* benefits. How can we resolve this conundrum? Although it is theoretically possible that *Q. marilandica* is declining throughout its range (there are no long-established permanent plots in the Cross Timbers) historical accounts indicate no great changes in the composition of the Cross Timbers (Francaviglia 2000). If there is indeed maintenance of codominance, then *Q. marilandica* must somehow be favored. For example, Penfound (1968) observed that

Q. marilandica sprouted better than *Q. stellata* after wildfire. It is possible that the "acceleration of succession" may be temporary and will be offset by recruitment from seedlings or sprouts. We are continuing to monitor the longer-term effect of the tornado with respect to growth and recruitment. It is also possible that some climatic conditions favor *Q. marilandica*; we are currently assessing this using tree rings. Such information should help us understand the nature of codominance.

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Table 1. Number of stems and basal area of alive stems before and after the tornado in the all forest modules (611 forest modules). The modules where damaged trees were bulldozed were not included. Alive stems had living tissues above 1.4m.

Species	Before the tornado		After the tornado	
	Number of stems	Basal area (m^2/ha)	Number of stems	Basal area (m^2/ha)
Quercus marilandica	1603	7.951	1047	5.263
Quercus stellata	1322	6.676	1257	6.212
Crataegus crus-galli	262	0.214	232	0.175
Prunus mexicana	117	0.153	112	0.147
Celtis occidentalis	21	0.092	21	0.560
Fraxinus pennsylvanica	9	0.073	9	0.449
Carya illinoensis	10	0.043	9	0.043
Sideroxylon lanuginosum	7	0.038	7	0.038
Sapindus saponaria	39	0.034	39	0.209
Urumus rubra	1	0.020	1	0.020
Carya texana	3	0.018	3	0.018
Diospyros virginiana	13	0.016	13	0.016
Morus rubra	4	0.012	4	0.012
Cercis Canadensis	4	0.011	3	0.011
Quercus shumardii	1	0.010	1	0.010
Prunus serotina	4	0.005	4	0.005
Viburnum rufidulum	7	0.003	7	0.003
Cornus drummondii	9	0.003	9	0.003

Table 2. Logistic regression for stem mortality of *Quercus marilandica* (n = 1603) and *Q. stellata* (n = 1322) after the tornado in all forest modules. Species are entered as dummy variables; *Quercus marilandica* = 1 and *Q. stellata* = 0. * Species x DBH represents interaction between species and DBH.

Variable	Estimated coefficient	Wald χ^2	*p*-value
x (east to west)	0.029	2.068	0.150
y (south to north)	0.029	9.660	0.002
Xy	1.38 x 10^{-5}	0.035	0.851
x^2	-5.08 x10^{-4}	12.161	4.88 x 10^{-4}
y^2	-4.1$10^{-5}$	2.531	0.112
x^3	1.14 x10^{-6}	11.205	8.16 x 10^{-4}
y^3	-5.1 X 10^{-9}	0.038	0.846
x^2y	2.91 x 10^{-7}	2.255	0.133
xy^2	-1.8 x 10^{-10}	4.52 x 10^{-06}	0.998
DBH	0.092	10.199	0.001
DBH^2	-7.96 x 10^{-4}	3.257	0.071
Species	3.392	76.218	2.54 x 10^{-18}
*Species x _DBH_	-0.057	10.257	0.001
Intercept	-8.3895	39.349	3.5 x $^{-10}$

Table 3. Number of stems per damage categories in the 246 “damaged” modules containing more than 20% expected/predicted mortality stem. Dead stems had no living tissue above 1.4m. Severely damaged stems had more than 70 % loss of canopy branches. Moderately damaged stems had less than 70 % loss of canopy branches.

Species	Dead	Severely damaged	Moderately damaged	Undamaged	Basal area(m^2/ha)	
					Before the Tornado	After the Tornado
Quercus marilandica (n = 931)	512	138	147	134	11.6	5.45
Quercus stellata (n = 628)	58	33	83	454	7.63	6.49

Fig. 1

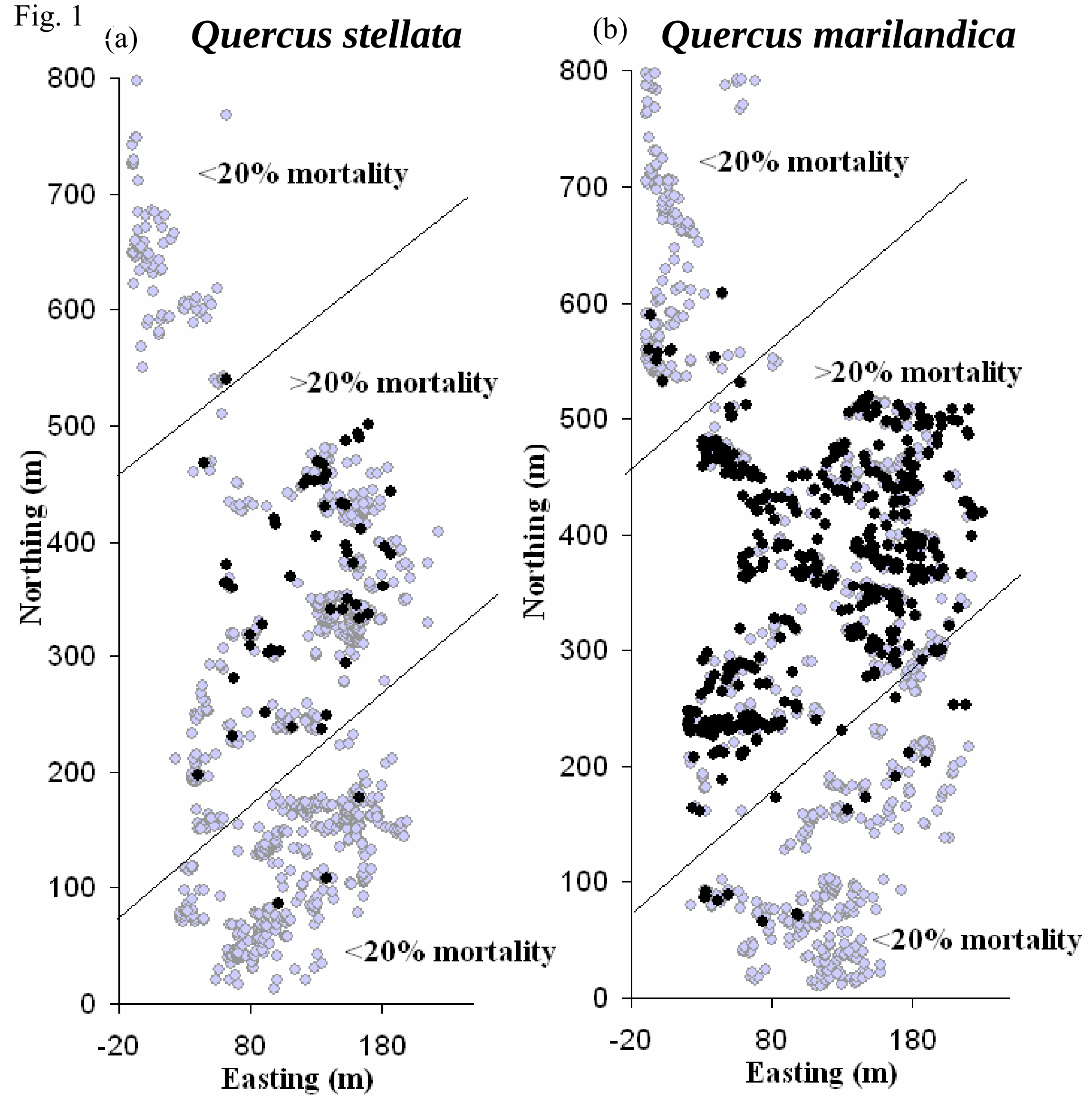

Fig.1. Distribution map of (a) *Quercus marilandica* and (b) *Q. stellata* in 14.48-ha study site. Bulldozed trees are not included. Gray closed circles represent live stems and black closed circles represent dead stems. Dead stems had no living tissues above 1.4m. We established the permanent plots along a north by south-eastern fence between the TGPP and adjacent private land.

Fig.2

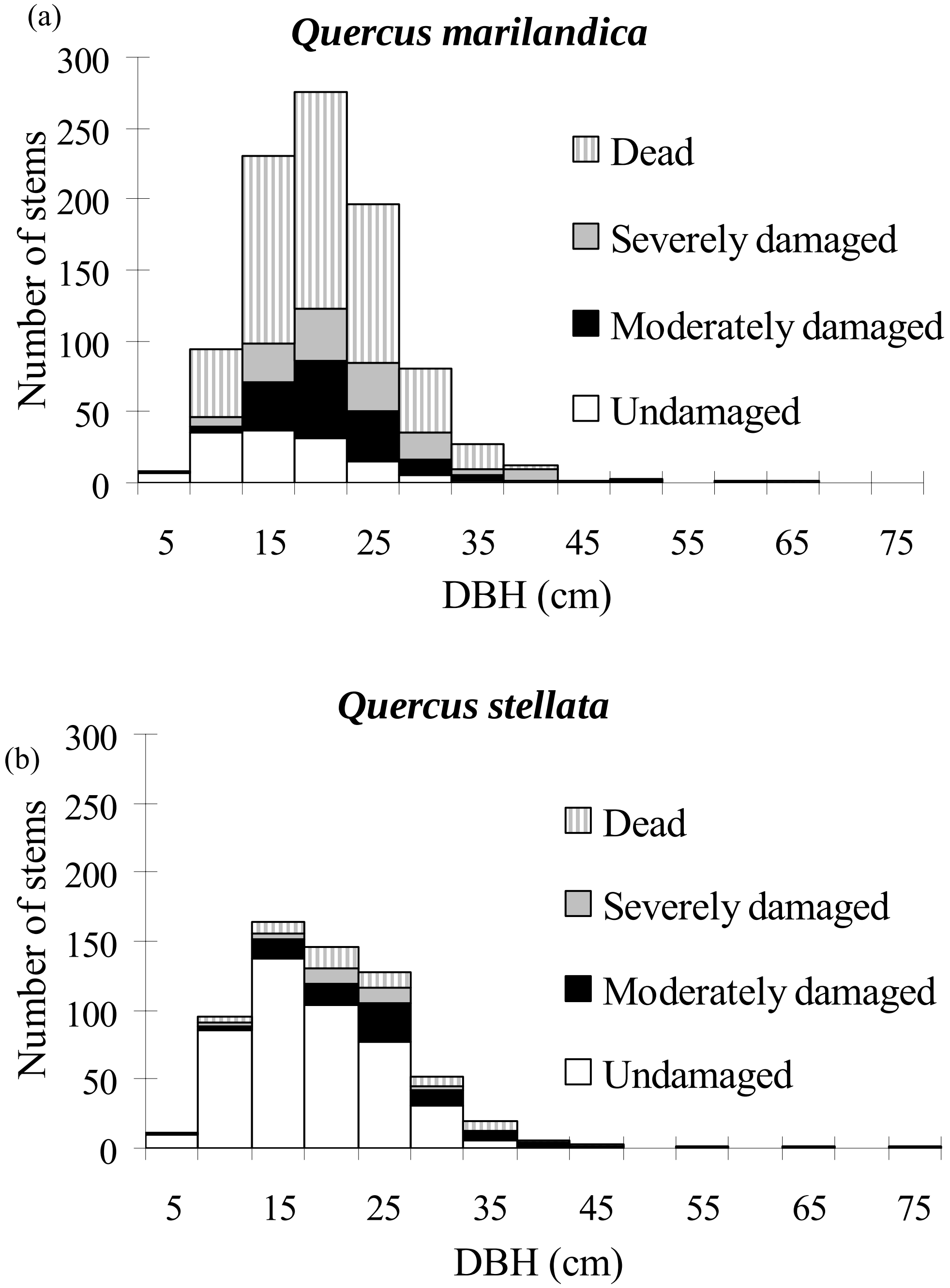

Figure 2. Diameter distribution with damage category for (a) *Q. marilandica* and (b) *Q. stellata* in the "damaged" 246 modules containing more than 20% expected/predicted mortality stem.

Fig. 3.

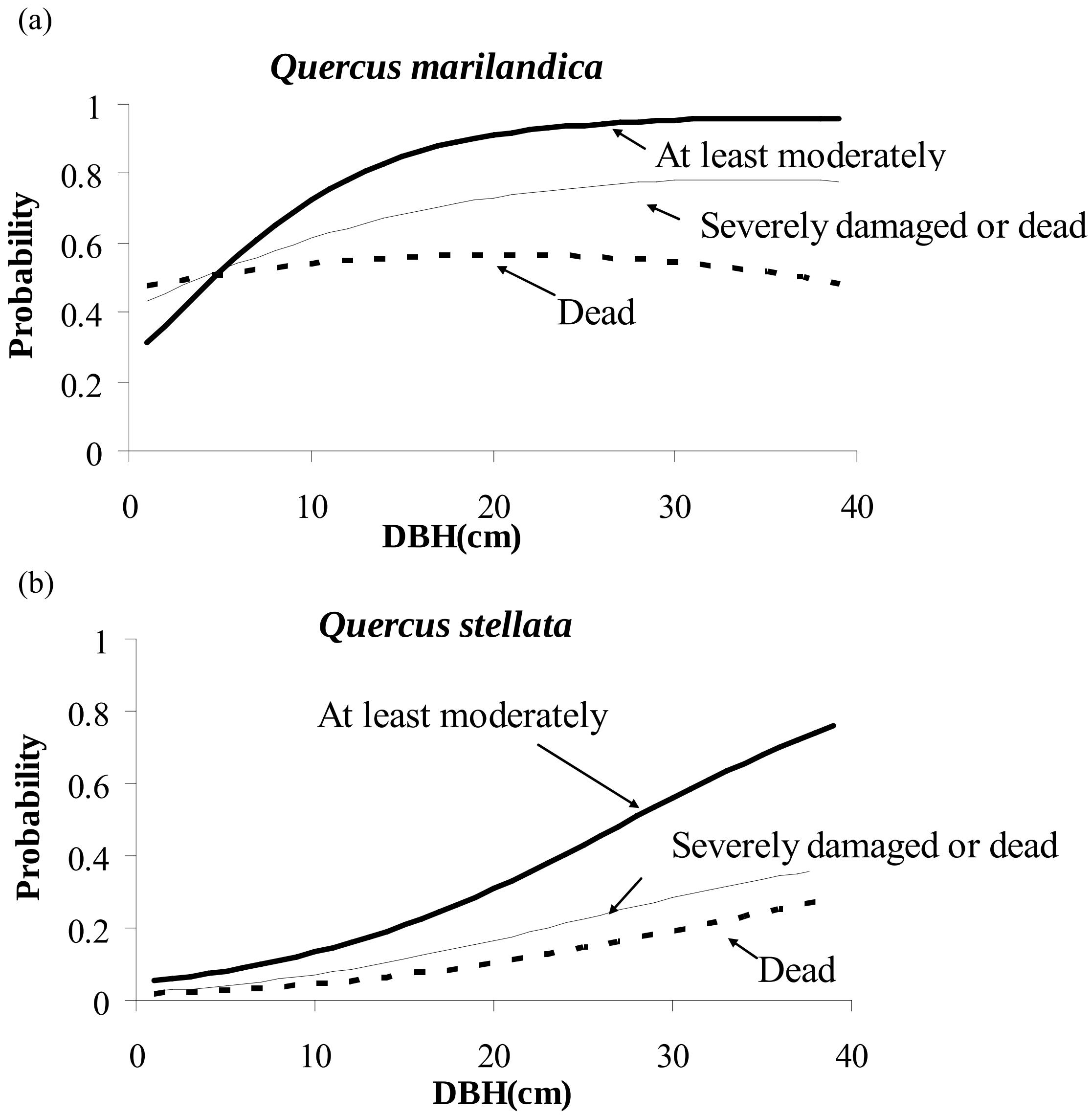

Figure3. Logistic regression (with DBH and DBH^2 as explanatory variables) showing the probability of trees being "at least moderately damaged" (bold line), "dead and severely damaged" (fine line), and "dead" (dotted line) in relation to the tree diameter (DBH in cm) for (a) *Q. marilandica* and (b) *Q. stellata* after the 2003 F3 tornado.

CHAPTER THREE

Fire history and seasonality of fire in a Cross Timbers forest, Tallgrass Prairie Preserve, Oklahoma

ABSTRACT: The Cross Timbers are a mosaic of savannas, grasslands and upland forests dominated by *Quercus marilandica* and *Q. stellata* and occupying a significant portion of the southcentral United States. Past fire history in the Cross Timbers has not been studied well, despite the prevalence of wildfire in the region. No pre-1993 documentation of fire history is available in the Cross Timbers of the Tallgrass Prairie Preserve, Osage County, Oklahoma. We created a fire chronology and examined fire return interval and seasonality of fire events using tree-disks of 72 *Q. marilandica* and 66 *Q. stellata,* killed by a 2003 tornado, in the preserve. These disks verified all known post-1993 fires; however, the percentage of disks that were scarred was low. We estimated a return interval of 1.35 years between 1947 and 1992. Most of fires appeared in the early spring, presumably because of fire prescribed for livestock forage on adjacent tallgrass prairies. Such land management may contribute to the shorter fire interval in the Cross Timbers compared with other oak forests in eastern United States.

*Index terms***:** Cross Timbers, Dendrochronology, disturbance, fire, *Quercus marilandica, Q. stellata*

INTRODUCTION

Fire, both natural and man-made, has played an important role in ecosystem and landscape function. It impacts structure and dynamics of vegetation and alters species abundance and composition (Anderson 1990, Abrams 1992, Jonson 1990, Glitzenstein et al. 1995, Pyne 1997, Brown et al. 1999, Dey and Hartman 2005, Abrams 2005). Components of the fire regime, such as fire-frequency and season of fire, are of critical importance in their effects on vegetation dynamics and species composition (Dyksterhuis 1948, Glitzenstein et al. 1995, Brown et al. 1999, Engle 2000, Dey and Hartman 2005).

In much of North America, fire favors oak-dominated forests. Many oak-dominated forests in the eastern United States have developed and been maintained by periodic fire for the last 8000 years (Abrams 1992, 2005, Rouse 1986, Cutter and Guyette 1994, Peterson and Reich 2001, Dey 2002). Periodic fire has promoted oak regeneration by sprouting or seed germination, while fire-susceptible competitors of oaks have been suppressed (Rouse 1986, Olson 1996, Dey 2002, Abrams 2005, Dey and Hartman 2005, Signell *et al*. 2005, Soucy *et al*. 2005). In addition to fire, windstorm is another important disturbance to affect structure of oak-dominated forests (Oliver & Larson1990; Peterson 2000). Dey (2002) reviewed effects of windstorms and fires on oak-dominated forests and concluded. Windstorms presumably decrease density of forest by removing overstory trees and may promote succession to shade-tolerant or pioneer species. However, fires suppress those competitors of oak species and a combination of windstorm and fire may promote oak regeneration. Since the fire suppression era of the 1900s, shade- intolerant oak species have been replaced by shade-tolerant species (Abrams 1992, 2005, Olson 1996, Abrams et al. 1998, Orwig et al. 2001, Signell 2005, Soucy *et al*. 2005).The Cross Timbers represent a notable exception (Abrams 1992, 2005, Clark 2003).

The Cross Timbers are a mosaic of grassland, savanna, and upland forest dominated by *Q. marilandica* and *Q. stellata* and occur at the transition between the eastern deciduous forests and the grasslands of southern Great Plains (Francaviglia 2000). They stretch from southeastern Kansas through Oklahoma and into central Texas (Küchler 1964, Therrell and Stahle 1998, Hoagland et al. 1999, Hoagland 2000). Two tree species, *Q. marilandica* and *Q. stellata*, dominate. Their short and stout stems combined with rocky, nutrient-poor soil prevented their commercial logging or clearance for cultivation (Therrell and Stahle 1999, Hoagland et al. 1999, Hoagland 2000). Therefore, relatively undisturbed tracts of ancient Cross Timbers, containing thousands of 200 – 400 year old *Q. stellata*, remain in Oklahoma (Stahle 1996, Therrell and Stahle 1998, Clark 2003, 2005).

Windstorm and fire are natural disturbances impacting the Cross Timbers. Fire, natural and/or anthropogenic, has affected species composition and abundance in the Cross Timbers (Forman 1948, Irving 1956, Penfound 1968, Pyne 1997, Hoagland 1999, Clark 2003). Fire-return interval and season of fire appears to impact the Cross Timbers (Bernardo *et al*., 1992, Engle *et al* 1996, Clark 2003). Historic fire regimes have been well studied in various vegetation types and regions including the eastern oak-dominated forests of the United States. However, the fire history of the Cross Timbers has not been studied well, although fire is purported to maintain the characteristic patchiness of the Cross Timbers (Forman 1947, Pyne 1997, Hoagland et al. 1999). Knowing past fire events in the Cross Timbers will help us to understand the role of fire in the ecology of this unique large ecosystem and allow us to compare it to other oak-dominated forests.

In this paper, we evaluate the past fire regime of the Cross Timbers in the Tallgrass Prairie Preserve (TGPP), Osage County, Oklahoma, using tree-disks of *Q. marilandica* and *Q. stellata*, killed by a 2003 tornado. No pre-1993 documentation of fire history is available in the study area. Our objectives of this study were i) to create a fire chronology using *Q. marilandica* and *Q. stellata*, ii) to examine how reliably *Q. marilandica* and *Q. stellata* record post-1993 fire events, and iii) to examine fire return interval and season of fire events prior to 1993.

STUDY AREA

The 15,783-ha TGPP (between 36.73° and 36.90°N latitude; 96.32° and 96.49°W longitude) is located in Osage County in north-eastern Oklahoma and has been managed by The Nature Conservancy (TNC) since 1990 (Hamilton 1996). Approximately 90% of the TGPP is composed of grasslands and the remaining is primarily forest. Most of the forest is the Cross Timbers dominated by *Q. stellata* and *Q. marilandica* (Palmer et al. 2003). Mean annual precipitation is 101cm and mean annual winter and summer temperatures are 3.9°C and 26°C, respectively (Oklahoma Climatological Survey 2006). The TGPP exhibits rolling topography and its elevation ranges from 253m to 366m

(Palmer et al. 2003). Cattle and bison graze the area. TNC has used randomized prescribed fire to maintain the grassland since 1990 (Hamilton 1996). More recently acquired properties on the TGP, including the study area, have been managed by TNC since 1993. The study area is currently grazed by cattle and it was burned in April 1994, April 1996, March 1997, March 1998, April 1999, April 2000, and August 2002. No documentation of fire history before TNC ownership is available.

METHODS

Data sampling

A tornado struck part of the TGPP and severely damaged the Cross Timbers located on the western edge of the TGPP in May 2003 (Shirakura *et al*. 2006). Killed or uprooted trees near the preserve boundary were bulldozed and piled alongside an access road to allow vehicular access. From these piles, we selected trees from a 70m x 470m area that were safely accessible, and obtained disks using a chainsaw in June 2004. We cut *Q. marilandica* (*n* = 84), *Q. stellata* (*n* = 69), *Crataegus crus-galli* (*n* = 4), and *Carya texana* (*n* =3) at 30 cm from ground level, a height that maximizes reported fire scars (Smith and Sutherland 1999). We recorded spatial location (although the pre-disturbance location is unknown) and diameter at breast height (DBH) of each tree. Twelve *Q. marilandica* and 3 *Q. stellata* disks were excluded from analysis because of rotten interiors. Thick bark insulates trees from the heat of fire and prevents trees from scarring (Sutherland and

Smith 2000, Guyette and Stambaugh 2004). Bark thickness of *Q. stellata* is positively related to its diameter, radial growth rate, and age (Guyette and Stambaugh 2004). Therefore, increasing diameter of *Q. stellata* decreases probability of scarring (Guyette and Stambaugh 2004). We collected samples of various diameters at breast height (DBH) to minimize missing fires (Fig. 1).Trees were collected without regard to externally visible fire scars.

Dendrochronology

We dried and sanded tree disks progressively using 80 - 400 size grit sand belts, 600 - 900 size grit hand-sand papers and fine steel wools. A fire scar is defined as the death of the vascular cambium due to excessive heat. It is associated with abnormal vessel formation and callus tissue that is undifferentiated thin-walled cells containing little lignin (Smith and Sutherland, 1999, 2001, Clark 2003). We identified fire scars using these characteristics and bark-fissure pattern of scars (Guyette and Stambaugh 2004) (Fig 1). Of the sampled trees, only *Q. marilandica* and *Q. stellata* disks exhibited fire scars.

We developed a master chronology of both *Q. marilandica* and *Q. stellata* using skeleton plots of non-injured 20 *Q. marilandica* and 20 *Q. stellata* (Stoke and Simley, 1996). Most disks were cross-dated using the master chronology we developed for each species (Fritts, 1976, 1991, Stoke and Simley 1996). Due to small sample size of old trees, 4 disks more than a century old were cross-dated using *Q. stellata* chronologies from nearby the Keystone Lake and the Bluestem Lake in Osage County, Oklahoma, obtained from the International Tree-Ring Data Bank (NOAA 2006). Cross-dating allows us to identify absent or false rings, and date samples to the exact calendar year using the pattern of tree-rings (Fritts 1976, Stoke and Simley 1996).

Tree-ring widths were measured up to 0.001mm using the Velmex apparatus and MeasureJ2X software (Voorhees 2004). The data of ring widths were exported to COFECHA (Holmes 1983) to check the quality of cross-dating and accuracy of the tree-ring series (Holmes 1983, Grissino-Mayer 2001a).

Dated and seasonal occurrence of fire

All fire scars were dated to the exact calendar year and were examined for the seasonal occurrence of fire using the position of fire scars within the annual rings (Dieterich and Swetnam 1984, Caprio and Swetnam 1995) We categorized fire scars occurring on the first half of the early wood as “early early growing season fire” (EE season fire), on the last half of the early wood as “late early growing season fire”(LE season fire), on the late wood as “late growing season fire” (A season fire), and between the late wood and the early wood in a year as “dormant season fire”(D season fire). We used the category of undetermined season fire (U season fire) when the exact position of the fire scar could not be determined due to narrow annual rings, scar damage, or other reasons. We used a known record of prescribed fire in the TGPP since 1993 as reference for identifying presence and seasonality of fire events. According to this record, the position of the fire scar in early April occurred on the EE or the D season and in March occurred on the D season. Therefore, if D and EE season scars occurred in a same year, we assigned those dormant-season scars to the EE season fire.

Data analysis

We developed the fire chronology and analyzed the median fire return interval and the Weibull median fire interval (WMI) for all fire events and, separately, for moderate-scaled fires, defined as single fires recorded by more than 10% of total samples, including non fire-scarred disks, using FHX2 (Grissino-Mayer 1995, 1999, 2000, 2001). WMI is the fire return interval associated with the 50% exceedence probability of a modeled Weibull distribution of all fire intervals from a fire chronology. Fire return intervals are rarely normal distributed. Therefore, WMI is considered to be less biased than mean fire interval as an estimate of central tendencies in fire (Grissino-Mayer 1995, 1999, 2000, 2001b). FHX 2 tested Goodness-of –fit for the normal distribution and the Weibull distribution separately using the Kolmogorov-Smirnov (K-S) test. We created a graph of fire chronology using FHX2. Data before 1947 were not analyzed due to sample size constraints. Therefore, we analyzed fire return intervals between 1947 and 1992. We also performed a chi-square test in SPSS 14.0 for Windows (SPSS) to test whether *Q. marilandica* and *Q. stellata* were scarred by fires equally.

RESULTS

The pith date of most of disks was post-1943 and all samples were between 13 and 260 years old (Fig. 3, 4). Approximately 64% of *Q. marilandica* ($n = 72$) and 49% of *Q. stellata* ($n = 66$) had at least one fire-scar (Fig.2), although approximately 90% of the scars were not externally visible. We found no evidence that fire scarred *Q. marilandica* and *Q. stellata* differently ($\chi^2 = 3.325$, $p > 0.05$). Twenty-nine fire events periodically appeared in the area between 1947 and 1992 and made 202 fire scars on 78 disks (Fig.4). The fire return interval data of both all fire (K-S $d = 0.345$, $p<0.002$) and the moderate fire (K-S $d = 1.000$, $p<0.001$) were not normally distributed. We did not reject the Weibull distribution for all fire intervals (K-S $d = 0.135$, $p>0.456$) nor for moderate fire intervals (K-S $d = 0.368$, $p>0.811$). We therefore used the Weibull distribution to estimate fire return interval. Between 1947 and 1992, fire occurred in the area every 1.35 years and moderate fire appeared every 2.21 years (Table2).

The disks of *Q. marilandica* and *Q. stellata* verified all of the prescribed post-1993 fire events. However, the proportion of oaks scarred by post-1993 fire was very low. In addition, no *Q. marilandica* was scarred by the 1993 prescribed fire (Table 1). Approximately 80 % of fires occurred in D season or EE season. Fire-scar position of late March and early April prescribed fires by TNC appeared in the D season or the EE season. Therefore, the D or the EE season fires are likely to have occurred in spring season. In 1970, 1971, 1981, and 1983, fire appeared early spring season and summer or early fall season in a year.

DISCUSSION

We documented frequent fire in the Cross Timbers of the TGPP since 1947, although the percentage of scarred disks was low. Paulsell (1957) also observed low scarring rates for *Q. stellata* experiencing annual burning. Thick coarse bark of both species may have prevented such scarring (Iverson *et al.* 1999, Sutherland and Smith 2000, Guette *et al.* 2002). Therefore, fire frequency may be underestimated using thick-barked *Quercus* species in studies with a limited sample size.

Our pre-1993 fire chronology supports the oral accounts of fires by employees and an owner of former ranch (the Chapman-Barnard Ranch) in the area (Smith 1996). The 50,586ha-Chapman-Barnard Ranch, one of the largest ranches in Osage county, was established in the Tallgrass Preserve region since early the 20th Century and operated until TNC purchased the TGPP (Smith 1996, Warehime 2000). According to the employees and owner, the study area was burned every spring for more than 60 years to enhance forage production for cattle, though there is no formal documentation of these fires (Smith 1996). However, our fire chronology showed 16 years (not consecutive) without fire between 1947 and 1992. *Q. stellata* and *Q. marilandica* may not have been scarred because of their fire resistance, and/or lack of sufficient fuel to scar, managers may not have burned those years, or grassland fires may not have entered the Cross Timbers.

Most lightning-caused fires occur between summer and early fall in the Tallgrass Prairie of the southcentral United States (Komarek 1968, Hulbert et al. 1980), whereas prescribed fire is typically performed in the spring season. The majority of fires in our study are likely to have been prescribed to adjacent grasslands to promote forage for livestock. The few summer or early fall fires we detected might have been ignited by lightning.

The fire return interval in the Cross Timbers of TGPP is much shorter than those in other oak dominated forests in Ohio (Sutherland 1997), Wisconsin (Wolf 2004), Missouri (Cutter and Guyette 1994, Guyette et al. 2002, Guyette et al. 2003, Dey et.al. 2004), Pennsylvania (Singell et all. 2005), and Kansas (Abrams 1985). Some of those fire return interval were examined using *Q. stellata* (Guyette *et al.* 2002, Guyette et al. 2003, Dey *et al*. 2004). However, there is a possible bias: spatial extent and sample size affects estimated fire return interval and frequency (Falk 2004). Larger areas increase the probability of encountering multiple non-overlapping fire events, and more trees increases the likelihood of recording low-intensity fires. Compared with other studies, our study area was relatively small. Moreover, our tree samples were >4-8 times larger than in other studies. Therefore, we believe our short fire return intervals are real. Like our study, Clark (2003) also found short fire interval (2.0 years) in the Cross Timbers of southern Osage County, Oklahoma, although her sample size was similar to those oak-dominated forest studies in Missouri and Kansas.

Land management in Oklahoma may contribute to frequent fire in the Cross Timbers in contrast to other oak forests. In the 19th Century, Texas cattlemen and Kansas ranchers moved into Oklahoma prairies, then called Indian Territory, and obtained grazing leases for cattle. By the end of the century, cattle had become big business and approximately 117,000 head of cattle grazed in 275,590ha lease pastures in Osage County, a time when the county had a human population of only 15,332. A railroad established in 1917 accelerated expansion of land being grazed and increasing the number of cattle. Osage County became known as the "Cattle Empire" (Warehime 2000). Fire has been a routine tool for improving forage for cattle. As the Cross Timbers of Osage County are immediately adjacent to vast expanses of grazed tallgrass prairie, these forests may therefore have experienced frequent burns.

Many studies in oak forests reported fire frequency decreased after the Native American era (Abrams 1992, Dey *et al.* 2004, Signell *et al*. 2005, Soucy *et al*. 2005, Wolf 2004). We did not have enough disks to compare fire frequency of Native American era with that of post Native American era in the Cross Timbers. However, Clark (2003) found there was no period of fire absence since 1780 and more frequent fire occurred in the post-Native American era than in the Native American era in southern Osage County. It might be possible that fire frequency increased after Native American era in the Cross Timbers because of intensive human activities, such as the cattle business. However, the fire frequency of the Native American era might have been underestimated due to small sample size.

Clark (2003) found cohort establishments of *Q. stellata* and *Q. marilandica* appeared following fire events. Like in other oak forests in North America, natural disturbances, such as windstorm and fire might influence regeneration of *Q. stellata* and *Q. marilandica* in the Cross Timbers. Ongoing research on the response of Cross Timbers to a devastating tornado (Shirakura et al.2006), surveying permanently marked Cross Timbers stands, as well as an expanded fire history based on older trees at the Tallgrass Prairie Preserve, will help us understand how this unique vegetation type responds to disturbance.

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Table 1. Number of samples, % of fire-scarred disks, fire return interval and seasonality of fire in a fire year. Number of samples disks includes both fire-scarred and non fire-scarred disks. *QM* and *QS* represent *Quercus marilandica* and *Q. stellata*.

Year of fire event	Number of fire scars		Number of sample disks		Percent of fire-scarred disks	Fire return interval	Season of fire event
	QM	*QS*	*QM*	*QS*			
1952	0	1	27	41	1.5	.	D
1953	1	0	29	43	1.4	1	U
1954	1	0	31	45	1.3	1	U
1957	3	3	46	51	6.2	3	D
1960	1	1	59	59	1.7	3	U
1961	1	2	63	59	2.5	1	U
1963	2	2	63	63	3.2	2	D
1964	5	1	66	63	4.7	1	U
1966	1	1	67	63	1.5	2	A
1967	1	1	67	63	1.5	1	EE
1969	1	3	68	63	3.1	2	A
1970	1	2	68	63	2.3	1	LE, A
1971	5	7	68	63	9.2	1	EE, A
1972	1	1	68	63	1.5	1	D
1974	1	3	68	63	3.1	2	D
1976	2	4	68	64	4.5	2	A
1977	10	6	68	64	12.1	1	D
1978	1	1	68	64	1.5	1	EE
1979	5	12	68	64	12.9	1	D
1980	0	8	68	65	6.0	1	EE
1981	6	8	68	65	10.5	1	LE, A
1982	1	7	68	65	6.0	1	D, A
1983	16	12	68	65	21.1	1	EE, A
1984	6	2	69	65	6.0	1	EE
1985	4	6	69	66	7.4	1	EE
1986	1	3	71	66	2.9	1	EE
1988	2	4	71	66	4.4	2	D
1989	5	3	71	66	5.8	1	D
1991	9	5	72	66	10.1	2	EE
1993	0	2	72	66	1.4	2	D
1994	4	2	72	66	4.3	1	EE
1996	1	1	72	66	1.4	2	EE
1997	3	4	72	66	5.1	1	D
1998	1	2	72	66	2.2	1	D
1999	10	5	72	66	10.9	1	D
2000	1	4	72	66	3.6	1	EE
2001	8	6	72	66	10.1	1	EE
2002	1	1	72	66	1.4	1	A

Table 2. Fire return interval and number of fire events for all fire and moderate fire in 1947-1992 in the study area. Moderate fire is defined as a single fire recorded by more than 10% of total samples including non fire-scarred disks in the fire year.

	All fires	Moderate fires
Number of fire events	29.0	5.0
Median fire return interval	1.00	2.00
Fire frequency	0.72	0.56
Weibull median fire interval	1.35	2.21
Weibull fire frequency	0.74	0.51
Minimum fire interval	1.00	2.00
Maximum fire interval	3.00	6.00

Fig. 1.

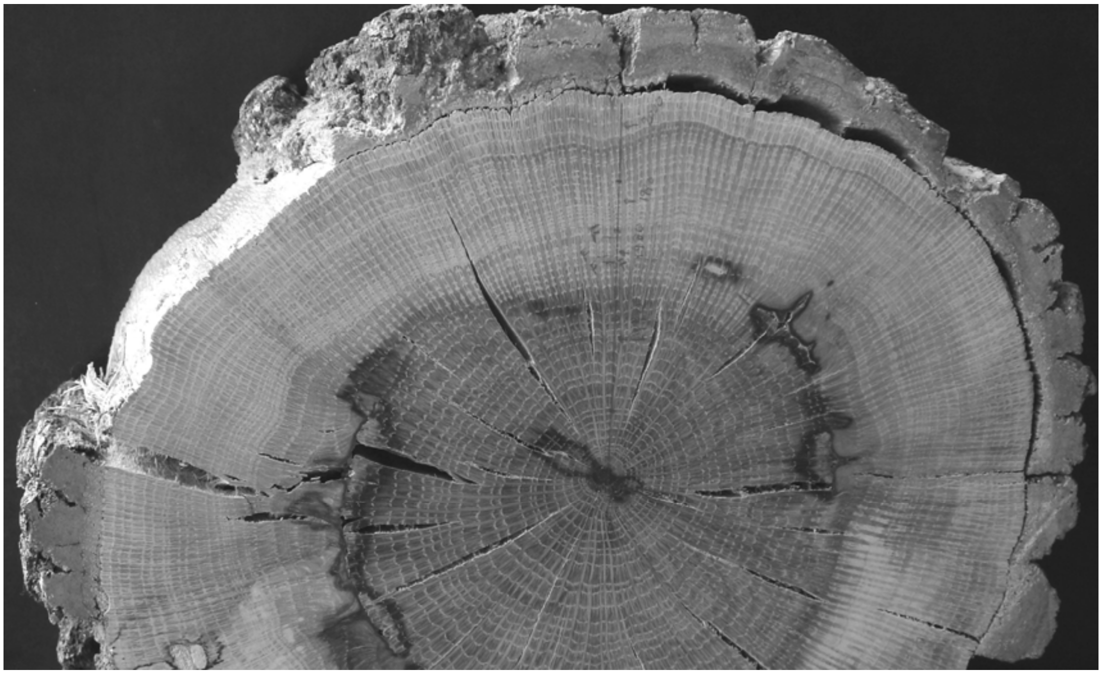
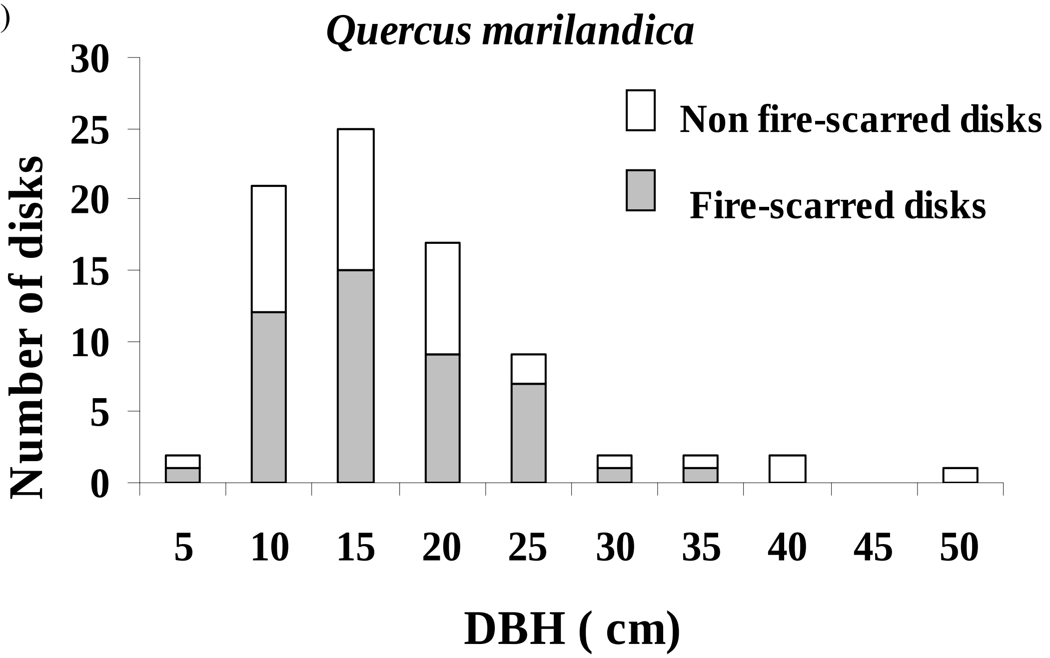


Fig. 1. A photograph of a fire-scarred *Q.stellata*.

Fig. 2.

(a)



(b)

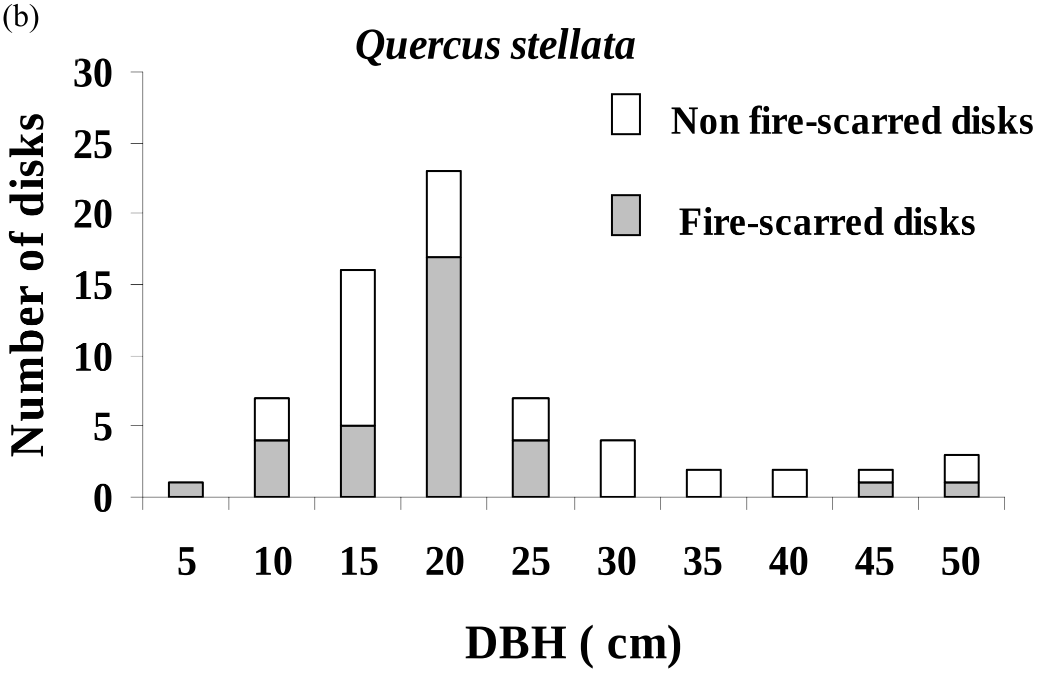


Fig.2. DBH distribution of fire-scarred and non fire-scarred disks for *Q. marilandica* and *Q. stellata*

Fig.3.

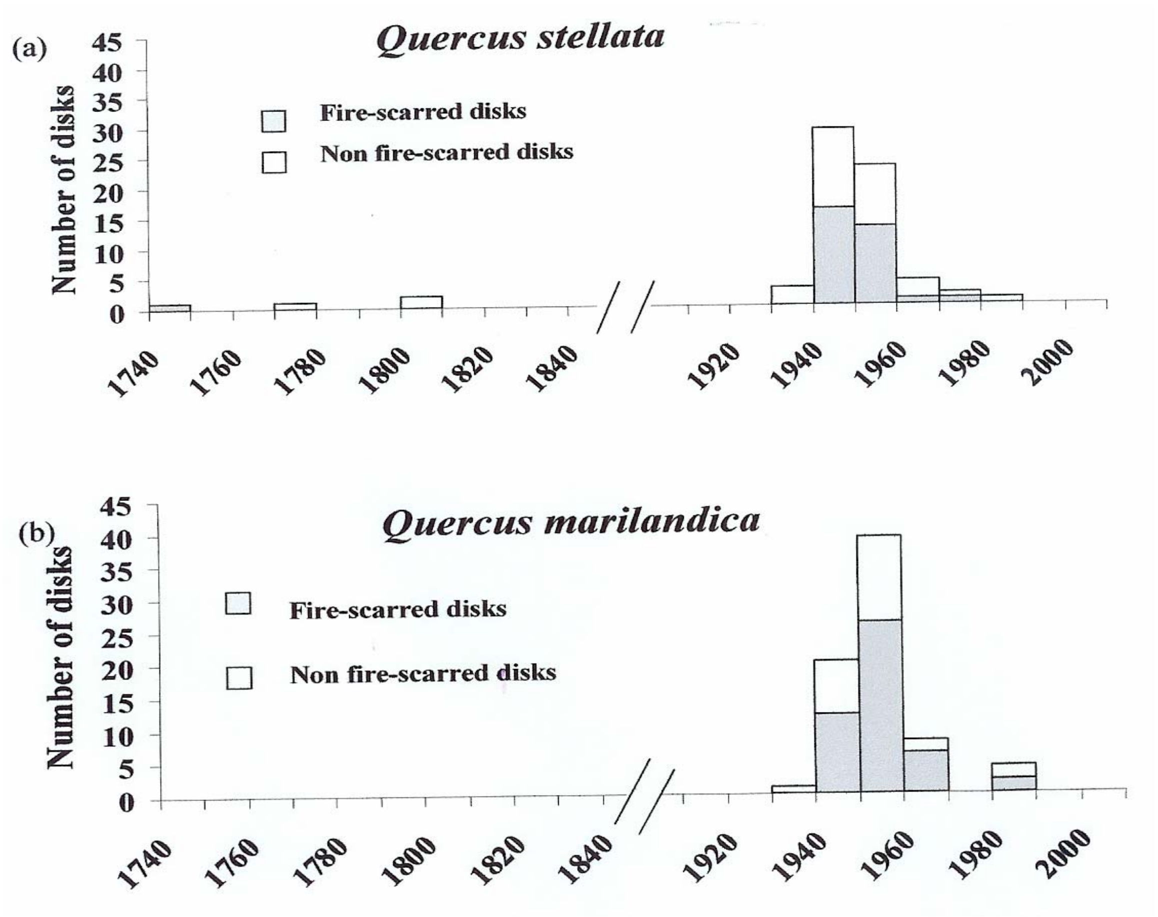


Fig. 3. Pith date distribution of fire-scarred and non fire-scarred disks for *Q. marilandica* and *Q. stellata*. All disks were dead by a 2003 severe tornado.

Fig. 4.

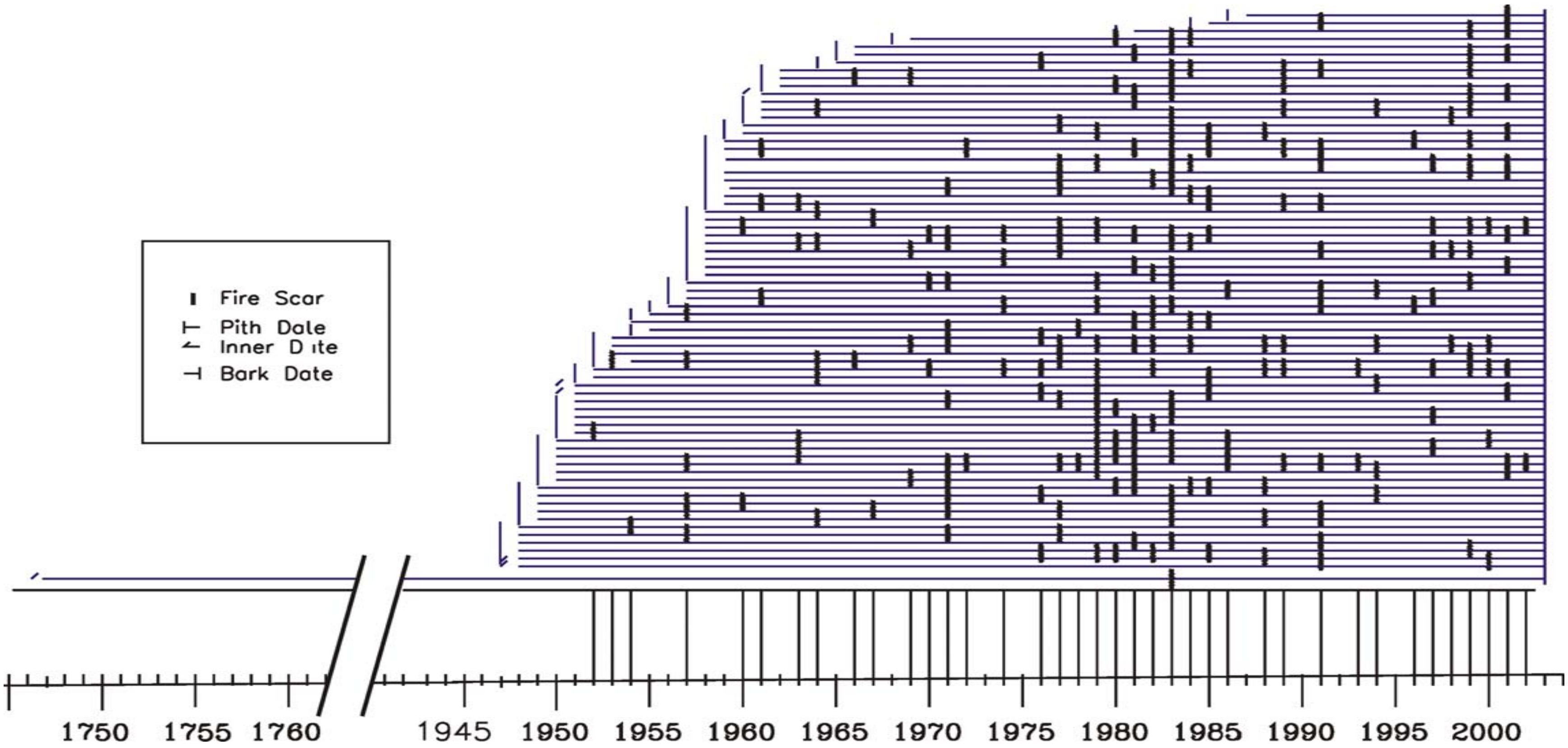


Fig.4. Fire chronology obtained from 74 fire-scarred disks in the TGP. Each horizontal line represents a tree-disk sample. Short vertical lines represent fire events and longer vertical lines at bottom of figure are the composite of all fire scars.

VITA

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Master of Science

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Title of Study: TORNADO DAMAGE AND FIRE HISTORY IN THE CROSS TIMBERS OF THE TALLGRASS PRAIRIE PRESERVE, OKLAHOMA

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Scope and Method of Study: The purpose of this research was to 1) examine how a severe tornado in 2003 affected the two dominant trees species, *Quercus marilandica* and *Q. stellata*, of the Cross Timbers with respect to damage and mortality and how such patterns varied as a function of tree size, 2) to reconstruct a fire chronology and examine seasonality of fire events and fire return interval using disks from trees killed by the 2003 tornado, and 3) to determine how reliably *Q. marilandica* and *Q. stellata* record fire events. We established a permanent plot where the tornado touched down 3 month after the tornado. We identified and recorded the diameter at breast height, spatial coordinates, and damage type for each tree. We tested our hypothesis using a chi-square test and logistic regression. Tree disks were collected in 2004 and cross-dated dendrochronologically. All fire scars were dated to the exact calendar year and were examined for the seasonal occurrence of fire using the position of fire scars within the annual rings.

Findings and Conclusions: Differences in species identity and tree characteristics, significantly affected tree mortality by the tornado. The tornado killed or damaged a significantly greater proportion of *Q. marilandica* than *Q. stellata.* Tree diameter clearly influenced the damage and mortality pattern in *Q. stellata*; larger trees sustained more damage and mortality. However, *Q. marilandica* did not exhibit size-dependent mortality. The tornado affected the two dominant species differently. The intra- and inter-specific differences in windstorm susceptibility may allow coexistence of the two species and are potentially important in the dynamics of the Cross Timbers. Fire appeared very frequently in the area between 1947 and 1992 and most of those fires occurred in the dormant or early spring season. Land management in Oklahoma may contribute to frequent spring fire in the Cross Timbers differently than in other oak forests. 138 *Quercus* disks verified all of the prescribed post-1993 fire events, Natural disturbance, such as windstorm and fire, might influence regeneration of *Q. stellata* and *Q. marilandica* in the Cross Timbers.

ADVISER'S APPROVAL: Michael W. Palmer