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Fire history of a prairie/forest boundary: more than 250 years of frequent fire in a North American tallgrass prairie

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Keywords
Cross Timbers; Dendrochronology; Fire history; Fire suppression; Osage Nation; *Quercus stellata*; Tallgrass prairie; Tree ring.

Abbreviations
EAS = Euro-American settlement; MFI = mean fire interval; TGPP = Tallgrass Prairie Preserve

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Abstract

Questions: Most modern fire-prone landscapes have experienced disruptions of their historic fire regimes. Are the primary tallgrass prairies of the Flint Hills reflective of a history of continuous fire occurrence? Did fire frequency, severity, size and seasonality change in connection with changes in land use? Has fire occurrence been related to drought conditions?

Location: Edges of Cross Timbers forest stands at the Tallgrass Prairie Preserve (TGPP) in the Flint Hills of Osage County, Oklahoma, USA.

Methods: Cross-sections of 76 *Quercus stellata* were collected from Cross Timbers stands at or near the grassland edge in the TGPP. Dendrochronological methods were used to identify years of formation for tree rings and fire scars. Superposed epoch analysis was used to evaluate the effect of drought conditions on fire occurrence.

Results: Fires were recorded in 46.6% of the years between 1729 and 2005. In 41 cross-sections at one site, the mean fire interval between 1759 and 2003 was 2.59 years, with fire interval decreasing from a mean fire interval of 3.76 years in the early part of the record to 2.13 years in modern times. No extended periods without fire were recorded in the study area. Drought conditions had no significant effect on fire occurrence.

Conclusions: In contrast with many fire-prone landscapes worldwide, the prairies of the Flint Hills have experienced no recent fire suppression or exclusion. Changes in fire frequency mark transitions in land use, primarily from being traditionally used by Native Americans to being managed for cattle production.

Introduction

Fire is an important disturbance in most world biomes (Bond et al. 2005). However, among major disturbance types, fire is unusual in the degree to which it can be manipulated and controlled by humans (Pyne 2001). Although humans have used fire for tens of thousands of years, capacity for large-scale control of fire is a modern phenomenon (Pyne 2001). This ability, coupled with negative perceptions about the effects of fire, resulted in widespread suppression or exclusion of fire (Pyne 2001; Mouillot & Field 2005).

Recent fire suppression or exclusion is broadly documented around the globe. Areas of the Campos vegetation of Brazil (Behling et al. 2007), Scandinavian forests (Arno 1998), eucalypt forests in Australia (Ward et al. 2001) and coniferous forests in China (Chang et al. 2007) have been influenced by recent fire suppression due to changes in human management or land use. The consequences of fire suppression can be large for biological systems, and may result in a loss of biodiversity, alteration of ecosystem function and changes in community structure and composition (Swetnam et al. 1999; Bond & Keeley 2005;

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Nowacki & Abrams 2008). Decreases in fire frequency can result in the accumulation of high fuel levels that can, in turn, generate fires of unprecedented intensity, increasing risk for both natural environments and human developments, and confounding efforts for ecosystem restoration (Varner et al. 2005). Not all areas have, however, experienced recent fire exclusion. Such places are, in general, characterized by a relatively undisrupted history of traditional management by indigenous peoples – for example, portions of the cerrados of Brazil (Mistry et al. 2005), some African savannas (Sheuyange et al. 2005) and portions of tropical savanna in northern Australia (Yibarbuk et al. 2001).

In North America, Euro-American settlement (EAS) marked a dramatic shift in fire occurrence. In many eastern areas, initial settlement brought a brief increase in fire occurrence as early settlers used fire to clear land for agricultural development (Guyette et al. 2002, 2003; Guyette & Spetich 2003). This initial pulse of fire was supplanted by an era of fire suppression when cultural attitudes shifted and settlers sought to protect their developments from fire (Guyette et al. 2002; Guyette & Spetich 2003). Within the North American Great Plains the pattern is much the same, the large expansion of woody species implies a reduction in fire occurrence in the post-settlement period (Bragg & Hulbert 1976; Steuter et al. 1990; Grant & Murphy 2005).

Prior to settlement, the Great Plains supported perhaps tens of millions of bison (Shaw 1995), which in turn supported the native peoples of the plains. Early historical accounts from settlers and explorers indicate that Native Americans ignited many grass fires on the prairies (Irving 1835; Higgins 1986). Although burning served many purposes (Russell 1983), it importantly served to facilitate bison hunting. Fresh growth available in recently burned patches serves to attract and concentrate animals (Coppedge & Shaw 1998), which would have facilitated hunting.

Within the Great Plains, the Flint Hills contain the largest (26 280 km^2) extant tallgrass prairies in North America (Samson et al. 2004). Tallgrass prairie, being the most mesic grassland system of the Great Plains, is particularly dependent on periodic fire to limit the establishment of woody plants (Axelrod 1985; Anderson 2006). The Flint Hills are primarily used for livestock grazing (Kollmorgen & Simonett 1965; Kindscher & Scott 1997) and are burned on a near annual basis to promote grass growth and control woody plant encroachment and enable livestock production (Hensel 1923a, b; Smith & Owensby 1978; Fuhlendorf & Engle 2001). Regular burning appears to have been a longstanding practice in the Flint Hills (Hensel 1923a, b; Smith & Owensby 1978), but the fire history of the region has not been fully characterized.

Although a few sites have yielded fire chronologies from charcoal sequences (e.g. Brown et al. 2005; Nelson et al. 2006), long-term fire patterns are generally not well-recorded in grasslands. However, dendrochronological studies of trees in or near grasslands have served as long-term proxy records in several prairie sites (e.g. Abrams 1985; Clark et al. 2007; Stambaugh et al. 2009). In the southern Flint Hills, grasslands form a mosaic with the ‘Cross Timbers’ forest. These forests are dominated by post oak (*Quercus stellata*) and blackjack oak (*Quercus marilandica*). The Cross Timbers region includes substantial amounts of original old-growth forest (Therrell & Stahle 1998). Generally, only extremely intense fires cause significant tree mortality in Cross Timbers forests (Engle et al. 1996), therefore, trees near the forest edge can serve as a long-term proxy record of the prairie’s fire history.

In this study, we seek to use dendrochronological data to address the following questions: (1) Has fire occurrence in the Flint Hills region been continuous or have there been periods of fire suppression or exclusion? (2) Were changes in fire frequency correlated with changes in human culture and land use? (3) Have climatic conditions (drought) played a significant role in fire occurrence? This study expands on previous tree ring-based Flint Hills fire history reconstructions of Abrams (1985) at the Konza Preserve in the northern Flint Hills and Shirakura (2006) at the TGPP by developing a multi-century chronology.

Methods

Site description

The Nature Conservancy’s TGPP was established in 1989 and is north of Pawhuska in Osage County, Oklahoma (36°56′N, 96°25′W) (Fig. 1). The TGPP’s 15 800 ha make it the largest protected area of tallgrass prairie in North America. Situated in the southern Flint Hills, the topography of the preserve is characterized by rolling hills. The limestone- and sandstone-derived soils of the preserve are thin and rocky, which precluded widespread cultivation in the region (Kollmorgen & Simonett 1965). The climate is continental, with annual precipitation averaging 94 cm and monthly average temperatures ranging between $-4\,^{\circ}C$ and $33\,^{\circ}C$ over the course of the year. The preserve’s grasslands are dominated by C_4 grasses, including *Andropogon gerardii*, *Schizachyrium scoparium*, *Sorghastrum nutans* and *Panicum virgatum*. Approximately 10% of the preserve is Cross Timbers forest dominated by *Q. stellata* and *Q. marilandica*.

Within the Flint Hills region, the most widespread land and cattle management system consists of annual burning followed by double-stocked livestock (Smith & Owensby 1978). Uniformly applied, this practice homogenizes

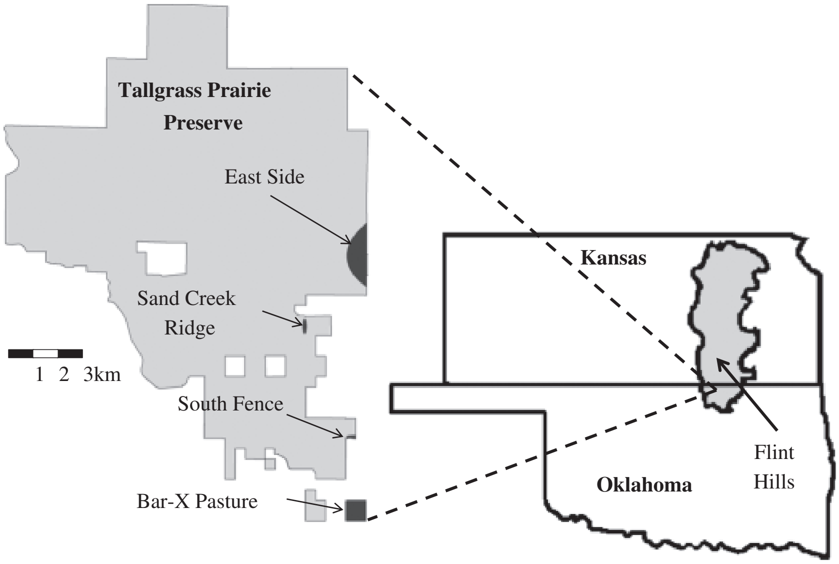

Fig. 1. Map of the Flint Hills region, TGPP and sample locations. Note: sample areas indicated on the map are approximate outlines.

much of the Flint Hills landscape (Fuhlendorf & Engle 2001). In contrast, the TGPP is managed with a randomized prescribed fire program (Hamilton 2007). On average, fire occurs on a 3-year rotation, where 40% of the burns occur during the dormant spring season, 20% during the summer, and 40% during the dormant autumn (Hamilton 2007). The preserve's bison unit is grazed by approximately 2700 animals (Allen et al. 2009). Cattle are also allowed to graze on the preserve as part of ongoing cattle management research (Hamilton 2007; Allen et al. 2009). The overall management goal at the TGPP is to maintain a heterogeneous landscape capable of supporting a full complement of tallgrass prairie biodiversity (Hamilton 2007).

Site history

The TGPP was historically and is presently within the domain of the Osage Nation. In pre-EAS times, the tribe was primarily centralized in the Ozark Plateau to the east of the TGPP, but the Osage annually travelled to the western prairies to hunt bison and other game (Wilson 1985; Burns 2004). In 1832, American author Washington Irving vividly documented the Osage hunts, including observations of nine separate instances where Osage hunters set fire to the prairies (Irving 1835).

Beginning in the early 1800s, increasing pressure from European and American settlers forced the Osage and other tribes into a series of land concessions. In 1826, the Osage were removed to a reservation in southern Kansas. Lands including the TGPP were allocated to the Cherokee in the 1830s (Burns 2004), but transferred back to the Osage in 1873. The study area is still partially under the jurisdiction of the Osage Nation.

The mid- to late 1800s saw the regional extirpation of bison, the introduction of cattle, the discovery of oil on the reservation and increased settlement. The Osage reservation's first cattle leases were authorized in 1883 (Burrill 1972). The Chapman-Barnard Ranch, established in 1915, encompassed up to 400 km^2 including the study area (Warehime 2000). The Chapman-Barnard Ranch used prescribed fire to improve pasture forage (Hamilton 2007). In 1989, a portion of the ranch was purchased by The Nature Conservancy, marking the establishment of the TGPP.

Data collection and analysis

We collected 76 full or partial *Q. stellata* cross-sections from the TGPP between 2006 and 2009 to use for our assessment of the TGPP's fire history. We cut cross-sections from dead trees that were knocked down during the installation of the preserve's bison fences. We also opportunistically collected samples from stumps or snags throughout the preserve. All samples collected were within 500 m of the prairie/forest edge. Cross-sections were cut within 30 cm of ground level in order to capture the most fire scars. Since *Q. stellata's* probability of scarring decreases with increasing diameter (Guyette & Stambaugh 2004), we sampled as wide a range of diameters as possible to minimize potential biases. We recorded universal transverse mercator (UTM) co-ordinates for each sample. Our samples were drawn from all the forested portions of the preserve, but most of the samples came

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from four areas (Fig. 1): East Side ($N=41$; 1.3 km^2), Bar-X Pasture ($N=14$; 0.3 km^2), Sand Creek Ridge ($N=4$; 0.02 km^2) and South Fence ($N=5$; 0.01 km^2).

Cross-sections were surfaced using an electric planer and belt sander to reveal the cellular structure of the tree rings and fire scars. We determined calendar years by cross-dating tree rings using the skeleton plot technique (Stokes & Smiley 1968) and then measured the tree-ring widths with a Velmex measuring stage. We used the measurements to validate the accuracy of our dating using the program COFECHA (Holmes 1983). Fire scars were identified based on the presence of callus tissue and cambial injury (Smith & Sutherland 2001) and then assigned to the first year of growth response present in the wound. Seasonality of fire scars was determined based on the position of the scar within the ring and were classified as dormant (between rings), earlywood, latewood and undetermined.

We used the FHX2 program (Grissino-Mayer 2001) to summarize fire scar statistics and graph and analyse fire events and fire return intervals for the preserve. We computed the mean fire return interval (MFI) for each site and the preserve as a whole. Additionally, since fire interval distributions are usually skewed, we used Kolmogorov-Smirnov goodness-of-fit tests to determine if the Weibull distribution modelled fire intervals better than normal distributions. We also used the Weibull model to calculate the upper and lower exceedance intervals that delimit significantly short or long fire intervals. Size of sampling area is important in fire history reconstructions since more fire events are typically encountered with increasing area. At approximately 1.3 km^2, the East Side site is comparable in area and sample size to other sites in the Cross Timbers region that researchers have assessed for fire history (e.g. Clark et al. 2007; Stambaugh et al. 2009); therefore the East Side site will be the focus of several of our analyses.

Following Guyette et al. (2003) and Clark et al. (2007), we calculated a fire index for the East Side site in order to assess changes in fire frequency through time. This fire index compensates for changing sample size through time. In this study, as with most fire history studies, more recent periods tend to be better represented than older periods. In order to compensate for this temporal bias, we calculated the fire index by dividing the number of fire scars in each decade by the total number of trees in that same interval.

Sample size and time period covered was limiting for several sites, therefore we restricted our analysis of temporal change in fire intervals and severity to the preserve as a whole and samples collected at the East Side site. In order to statistically evaluate changes in fire intervals through time, we calculated fire intervals for four time periods: 1) traditional use period (pre-1826) – Osage were likely using the land in a more or less traditional manner, 2) population flux period (1826-1870) – corresponds with Osage removal to Kansas and replacement by the Cherokee, 3) transitional period (1871–1914) – corresponds with the return of the Osage, the extirpation of bison, the introduction of cattle, the discovery of oil and increasing EAS, and 4) ranching period (1915–1989) – era of the Chapman-Barnard Ranch. We also more broadly assessed pre-EAS and post-EAS fire intervals. We transformed our fire interval data to a standard normal distribution and performed t-tests ($\alpha=0.05$) to determine if MFI differed between pre- and post-EAS. Similarly, we tested for a significant difference between the traditional use period, and all subsequent periods defined above. We also tested changes in fire severity, defined as change in percentage trees scarred for the different time periods.

Climate can also have an important effect on a region's fire regime. We used superposed epoch analysis (Grissino-Mayer 2001) to determine the influence of regional droughts on fire event occurrence. Drought data were derived from long-term reconstructions of Palmer drought severity indices (PDSI; Cook & Krusic 2004). We bootstrapped data for 1000 simulated fire events in order to derive confidence limits. We assessed a 10-year window around each fire event (6 years preceding and 4 years succeeding) in order to determine if drought was significantly different from the average during the time span. We performed superposed epoch analysis on data from the East Side site on all fire events recorded by at least two trees.

Results

The tree-ring record we recovered from post oaks in this study spanned 277 years (1729–2005). Individual tree time spans ranged from 60 to 244 years (mean = 116 years). Intercorrelation between tree-ring series was 0.622, with a mean sensitivity (year-to-year variability) of 0.346. For the whole preserve, we identified a total of 292 fire scars occurring in 129 (46.6%) of the years (Fig. 2). Of the 255 fire scars that we were able to identify to season, 76.9% occurred during the dormant season, from approximately mid-August to early March. The majority of growing season fire scars (14.5% of total scars) occurred in the earlywood, indicating early to mid-spring fires. The remaining 8.7% of fire scars occurred later in the growing season.

Fire intervals

At the TGPP, fire was present throughout the period of record (Fig. 2). In the East Side site, there were only 10 intervals between fire that exceeded 5 years and only two

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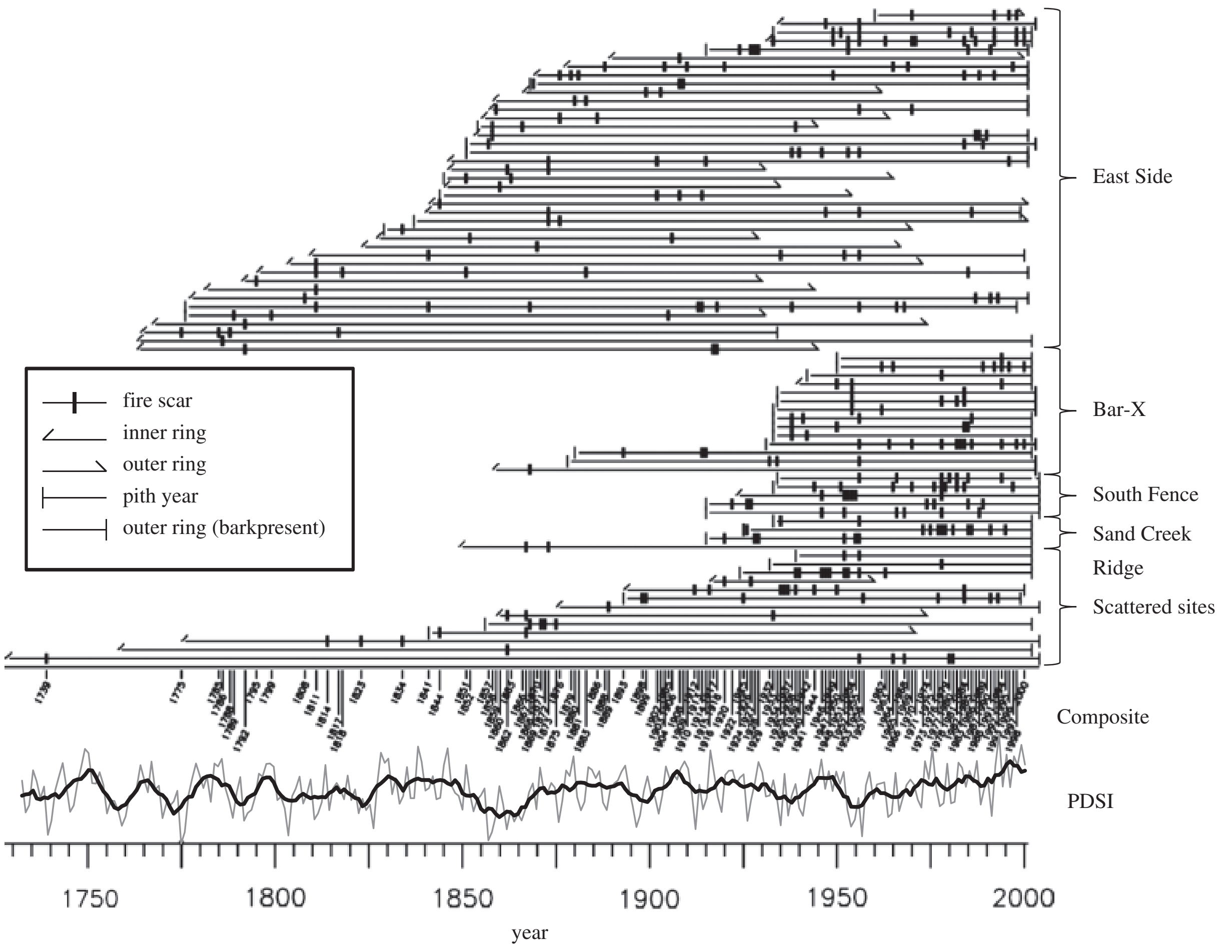

Fig. 2. Fire history chart for the TGPP. Each horizontal line represents an individual tree record at a given site. Samples for each site are indicated in brackets along the right side of the graph. The composite record indicates every fire occurrence at the TGPP. PDSI for the region is illustrated below the composite line, and is highlighted with a 7-year running average.

that exceeded a decade (Fig. 3a). Intervals of 1 year were most common in the composite record for the East Side site (Fig. 3a), although point samples (individual trees) tended to experience longer intervals (Fig. 3b). This pattern is consistent with that observed by Shirakura (2006), where only about 5% of tree samples were scarred by a given fire. For the East Side site, the upper exceedance interval was 5.12 years and the lower exceedance interval was 0.52 years. Intervals outside of that range are considered significant outliers.

Fire index values fluctuated throughout the period of record (Fig. 4); these fluctuations generally correspond with changes in human culture and/or land use. With the end of the traditional use period in the 1820s there is an abrupt cessation of fire, followed by a gradual increase in fire, followed by another cessation in the 1890s – the middle of the transitional period. The first cessation is coincident with the Osage's removal to their Kansas reservation. The second cessation is coincident with the establishment and expansion of ranching on the reservation. Fire persisted throughout the twentieth century.

For the whole preserve and the four included sites, MFI for periods of record ranged from 2.04 to 6.74 years (Table 1). Kolmogorov-Smirnov tests determined that the Weibull distribution adequately describes fire intervals for the preserve and individual sites. The Weibull median interval ranged from 1.72 to 3.87 years (Table 1). Due to limited sample size at some sites, we only assessed temporal changes in fire intervals for the entire preserve and for the East Side site. Fire intervals were significantly different in the pre-EAS and post-EAS periods (Table 2). Most of the change in MFI at the preserve occurred during the transitional and ranching periods (Table 2). Changes in severity of fire as determined by percentage of trees scarred were also significantly different between early periods and late periods, likely indicative of a shift towards patchier or less intense fires (Table 2).

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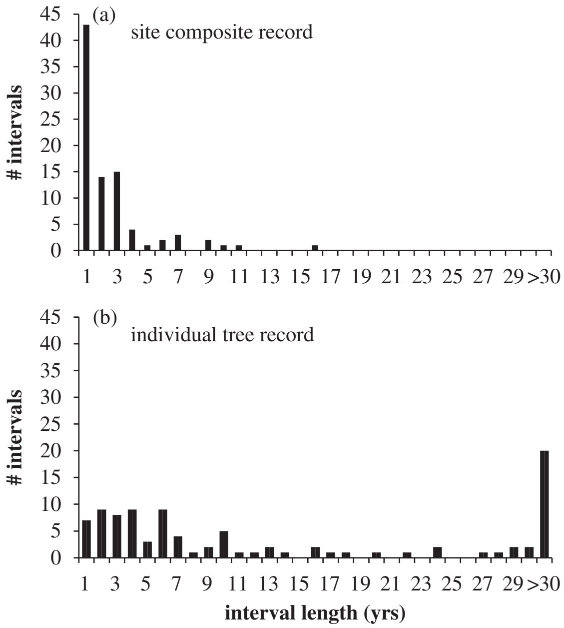

Fig. 3. Distribution of fire intervals from all samples collected at the East Side site ($N = 41$) for both the (**a**) site composite record and (**b**) individual tree record.

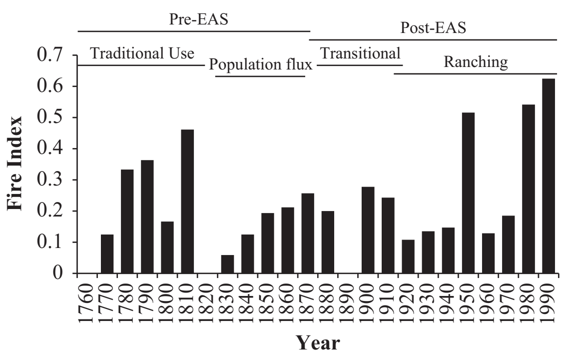

Fig. 4. Fire index for the East Side site at the TGPP. Higher index values indicate more fire events. Lines above the chart indicate the time spans of the different historical and cultural periods assessed in this study.

Fire and drought

Superposed epoch analysis revealed no significant relationship between fire events and drought. Although no general pattern was evident, several years appeared to have unusually widespread fires (more than four trees recording fire scars) in years of moderate to severe drought. Notable years where fire events and drought conditions coincided were 1812, 1874, 1939, 1953 and 1957. Since the late 1970s, however, well-recorded fires tended to occur more in years of wetter than average conditions, notably 1979, 1985, 1986, 1993 and 1995.

Discussion

Anthropogenic burning is an ancient practice (Pyne 2001) that has shaped the flora and fauna of grass-dominated ecosystems around the globe. Some of the most diverse grass-dominated systems are those that are managed in a traditional mode or in a way that emulates aspects of traditional management. For example, in northern Australia, unmanaged fires burn unchecked across vast portions of

Table 2. Temporal change analysis for MFI and percentage samples scarred (as a proxy for widespread and/or intense fires). Values in parentheses indicate standard error. *Indicates significance with either Pre-EAS or traditional use period from *t*-tests at $P < 0.05$.

Time Span	Description	All Sites ($N = 76$)	East Side ($N = 41$)
Mean fire return interval			
1770–1871	Pre-EAS	3.36 (0.55)	3.76 (0.74)
1871–2005	Post-EAS	1.33* (0.08)	2.13* (0.25)
1770–1825	Traditional use	3.69 (0.79)	3.91 (0.95)
1826–1870	Population flux	2.5 (0.60)	2.69 (0.62)
1871–1914	Transitional	1.72* (0.22)	2.39 (0.55)
1915–1989	Ranching	1.21* (0.08)	2.24* (0.34)
Percentage scarred			
1770–1871	Pre-EAS	8 (0.94)	8.79 (1.26)
1871–2005	Post-EAS	4.45* (0.37)	5.65* (0.55)
1770–1825	Traditional use	10.44 (1.53)	13.17 (2.00)
1826–1870	Population flux	5.71* (0.80)	5.03* (0.66)
1871–1914	Transitional	3.17* (0.45)	4.19* (0.61)
1915–1989	Ranching	4.77* (0.54)	5.8* (0.82)

Table 1. Descriptive statistics and fire intervals for sites at the TGPP.

	All Sites	East Side	Bar-X Pasture	South Fence	Sand Creek Ridge
Years of Coverage	1729–2005	1759–2005	1859–2004	1916–2005	1850–2003
Number of Sample Trees	76	41	14	5	4
Total Intervals	128	87	27	26	19
Mean Fire Interval	2.04	2.59	4.89	2.88	6.74
Weibull Median Interval	1.47	2.05	3.31	2.18	3.87
Minimum Fire Interval	1	1	1	1	1
Maximum Fire Interval	36	16	25	17	47
Lower Exceedance Interval	0.3	0.52	0.61	0.5	0.54
Upper Exceedance Interval	4.21	5.12	10.22	5.85	14.33

the tropical savanna during the dry season each year, negatively affecting fire-sensitive species and habitats (Yibarbuk et al. 2001). In contrast, Dukaladjarranj, an intensively fire-managed Aboriginal estate within the region, contains tropical savannas with high biological diversity, including rare species and threatened communities that are protected from high-intensity fires (Yibarbuk et al. 2001). As another example, until recently, Maasai pastoralists in East Africa propagated numerous small fires, creating a mosaic of burned areas with enhanced vegetation diversity that provided improved forage for cattle and protection to their settlements from intense dry season fires (Butz 2009). Recent changes in government fire policy, increased human population pressure and extended droughts have limited the Maasai's ability and inclination to continue their traditional burning practices, potentially jeopardizing traditional savanna vegetation (Butz 2009).

At the TGPP, fire occurrence and frequency also appears to be strongly tied to cultural history and land use. Marked changes in the TGPP's fire regime occurred during the transition from traditional hunting-driven land uses, to the establishment of the cattle industry. Compared with many other areas where recent changes in land use have led to fewer fires, if not outright suppression or exclusion, the Flint Hills are unusual in that fire has persisted as a regular component of landscape management. Although the details of fire's persistence in the region are not well known, Hensel (1923a, b) described burning as a longstanding practice amongst cattle producers in the region. With respect to the origin of this practice, Hensel (1923b) contended that 'it is within the realm of possibility to suppose that the white man copied this ancient custom [burning] on his farm pastures, using it for what he believed to be an advantage.'

The fire history observed at the TGPP is generally consistent with that observed at other sites in the tallgrass prairie/Cross Timbers region. In southern Osage County, Clark et al. (2007) observed a similar decrease in fire return interval frequency from 4.9 years to 2.1 years between 1772 and 2002. Shirakura (2006) also found near annual fire at another site in the TGPP during the latter half of the twentieth century, but did not reconstruct earlier fire regimes. In central Oklahoma, DeSantis (2010) observed a decrease between 1750 and 2005 in fire interval from 4 to 2 years in an old-growth Cross Timbers forest. In contrast, at a prairie edge in the western Cross Timbers, Stambaugh et al. (2009) observed a slight increase in fire interval length, from 4.4 to 5.1 years during the time period 1712–2006. Consistent with Clark et al. (2007) and Stambaugh et al. (2009), we observed lower percentages of trees scarred in the post-EAS period than in the pre-EAS period (Table 2). Although biases due to sample size and preservation in older time periods cannot be discounted, this regionally repeated pattern indicates an overall increase in fire frequency and decrease in fire intensity and/or size of fires in post-EAS periods. Also, consistent with the aforementioned studies, we did not find a strong relationship between fire and climate (drought) during the years around the fire event. This is not surprising given the high number of fire events observed at the TGPP.

Although fire has persisted in the Flint Hills region, changes in frequency and intensity of fire are likely to alter the dynamics and composition of its grasslands. As described above, the fire management program practiced at the TGPP is different from that employed on most lands within the Flint Hills region. Most landholders in the region practice the intensive-early stocking system (Smith & Owensby 1978), which consists of annual, early-spring fires followed by double-stocked cattle for 2.5 months. The annual burning, coupled with heavy grazing, results in a relatively homogenous landscape (Fuhlendorf & Engle 2001). The homogenized landscape has deleterious effects on grassland diversity, most notably for grassland birds (Fuhlendorf et al. 2006). In contrast, the TGPP's management plan emphasizes landscape heterogeneity, and applies fire, on average, every 3 years to randomly selected units. Given the random nature of the selection, some units may be burned more or less frequently, but most fires are likely to occur within the upper and lower exceedance intervals reported here (Table 1). Based on our results, it appears the TGPP's fire management practices more closely match the fire regime of the traditional use period prior to settlement than that currently practiced under the intensive early-stocking system.

Understanding a site's history is essential to understanding its current ecological status, as the legacies of past events and land uses can leave residual effects that may affect species assemblages, disturbance regimes and ecosystem dynamics, both currently and on into the future (Foster et al. 2003). The fire history of the Flint Hills region is largely shaped by anthropogenic factors, with fire varying in frequency according to different cultural periods and associated land uses. Although fire has persisted, the modern practice of near-annual burning appears to lack the variability that characterized the historic fire regime. Despite this, the continuous application of fire in the Flint Hills is likely a significant contributor to the maintenance of its prairies.

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