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Three centuries of fire and forest vegetation transitions preceding Texas' most destructive wildfire: Lost Pines or lost oaks?

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ABSTRACT

In 2011, the most destructive wildfire in Texas history (Bastrop County Complex Fire, BCCF) burned 34,000 acres including most of Bastrop State Park. We used dendrochronological analysis of vegetation paired with documentary information to reconstruct the historical fire regime, changes in forest composition, and possible human influences leading up to this seemingly unique event. In addition, demographics of fire-killed and immediate post-fire regenerating trees were determined through stem aging and a regeneration census. Historical fire frequency was lower during the pre-EuroAmerican Settlement period (pre-1830) compared to later time periods before the 1920s. Since the 1920s, fire occurrence has significantly decreased. Historical fire characteristics appeared to change with local and regional cultural and land use changes. Within the BCCF area were extensive areas of very old (up to 359 yrs old) open-grown post oaks (*Quercus stellata*) that had been overtopped by 60 year old loblolly pines (*Pinus taeda*). Historically, oak woodlands likely persisted in the study area due to recurring fire and, though less well documented, by grazing and selective logging for loblolly pines. This region is an ecotone between the oak woodlands and Lost Pines and our data show transitions between the two types through time. It is unclear how this vegetation interaction may have affected the destructive BCCF, but its severity and effects were unprecedented during at least the last three centuries. Little to no loblolly pine natural regeneration existed despite being dominant in the pre-fire forest overstory. Based on stump sprout abundance, blackjack oak (*Q. marilandica*) will likely be the dominant tree species in the next few decades.

1. Introduction

Throughout the twentieth century, a decrease in fire activity (i.e., fewer fires and less area burned) has been an underlying cause of vegetation change in the U.S. (Hardy et al., 2001). In the eastern U.S., vegetation changes included greater densities of trees and shrubs (DeSantis et al., 2010a; Hanberry et al., 2014; Stambaugh et al., 2014) and have led to increased fuel loading, less herbaceous species cover and diversity, and decreased fire-tolerant vegetation types, among others (Nowacki and Abrams, 2008, 2015). This trend of fire regime-vegetation change presents complex challenges for land management including natural community restoration, wildfire suppression and risk mitigation, and prescribed fire (Ryan et al., 2013).

Departures of current vegetation and fire regimes from historical conditions are detectable in natural and documentary archives (Swetnam et al., 1999). From these data, it is well known that vast areas of frequent fire forest communities (e.g., mean fire intervals $\leq$ 6 yrs) were present across the southeastern U.S. (Guyette et al., 2012), including areas as far west as Texas (Smeins et al., 2005; Stambaugh et al., 2014). Presently, the majority of Texas' natural vegetation (i.e., excluding agricultural, urban, and barren areas) is considered either moderately or highly departed from historical types and structures (Hann et al., 2004). Common forest examples of vegetation departures include expansion and increased densities of mesquite (*Prosopis glandulosa*) (Ansley et al., 2001), juniper (*Juniperus* spp.) (Engle et al., 2007), and yaupon (*Ilex vomitoria*) (Cathey et al., 2006). Little quantitative data characterizing historical fire regimes exists in Texas (Stambaugh et al., 2014) and this lack of information makes it challenging to envision the precedence for current vegetation and wildfire events (e.g., vegetation types, fuel loading, fire behavior, potential fire risk).

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In 2011, wildfires in the southcentral U.S. presented a higher potential and complexity than had been observed in recent history (Texas A & M Forest Service, 2012). The area, number, and behavior of wildfires (e.g., crown fire in conifer and deciduous forests) were somewhat unanticipated with areas burned being the highest in Texas (11,018 km^2) and Oklahoma (1187 km^2) since at least 2002 (source: National Interagency Fire Center, period: 2002–2015). Accentuated by drought, multiple high severity wildfires occurred across many vegetation types including grasslands, woodlands, and forests. In some of these fires, dominant vegetation types were altered or lost. To date, little research has been conducted to quantify and understand the historical precedence for these severe fires and their associated vegetation changes.

The objective of this study was to document historical changes in the fire regime characteristics and vegetation at Bastrop State Park, Texas (BSP) as context for the effects of the high-severity 2011 Bastrop County Complex Fire (BCCF). To do this, we used dendrochronological methods to reconstruct past fire events and tree establishment dates. Within the timeline of fire and vegetation changes, we integrated historical documents describing local and regional cultural and land use changes. We expected that this approach would provide a context for understanding the historical ecology within the region and provide insights into vegetation and land use history leading up to high severity fires.

2. Methods

2.1. Study site

The study site was located in southcentral Texas, U.S. in the southern portion of BSP (30.12°N, 97.31°W). BSP lies north and east of the Colorado River, a major watershed of central Texas covering 103,341 km^2. The climate is humid-subtropical with an average annual rainfall of approximately 94 cm and a mean annual temperature of 20 °C. Terrain throughout BSP is highly variable with both steep and flat terrain and substrates ranging from thin-soiled gravel ridges, to deep sands, to clays and sandy loams. Within the study area the topography is gentle (0–12% slope) with elevations ranging from 140 to 152 m a.s.l.

The 139 km^2 BCCF occurred from September 4 to October 10, 2011. The fire burned the majority of BSP and was the most destructive in Texas' history. Two lives were lost, over 1600 structures burned, and over $300 million in property damages incurred. Due to prolonged extreme drought conditions (September 2011 Palmer Drought Severity Index = −6.21, Texas Climate Division 7; NCDC, 1994), record high temperatures, and gusting winds in excess of 58 kph, large areas burned at high severity (Rissel and Ridenour, 2013; Brown et al., 2014). Within BSP, average tree scorch and char heights were 15.1 and 13.5 m, respectively (Keith and Creacy, 2011). Prior to the BCCF, the majority of BSP was comprised of closed-canopy forest with an overstory composition dominated by loblolly pine (Pinus taeda) and post oak (Quercus stellata). The entire area of this study burned at high severity, which is characterized as 100% top-kill of all vegetation, complete surface fuel consumption, and surface soil exposure and discoloration. Heavy rains in the weeks following the fire resulted in significant topsoil loss across BSP.

2.2. Fire history

To reconstruct the fire history of the area, we cut cross-sections from the ground level of 50 dead post oak trees (Fig. 1). Prior to sampling, trees were sounded using a hammer to evaluate whether the tree was hollow or rotten and were rejected if significant decay was suspected. To minimize fire scarring bias due to tree size and age, we sampled a range of small to large diameter trees with young to old ages (Guyette and Stambaugh, 2004). All trees were sampled within a 1-km^2 study area, tree heights were measured to the nearest decimeter, and tree locations were recorded using a global positioning system (GPS). This study area size is comparable to many other studies across the eastern U.S. which facilitates comparisons of fire regime characteristics (Stambaugh et al., 2016).

In the laboratory, cross-sections were prepared by sanding with progressively finer sandpaper down to 1200 grit. All tree-ring widths were measured in sequence at 0.01 mm precision and dated using standard dendrochronological techniques (Stokes and Smiley, 1968). Crossdating of ring-width series utilized existing post oak ring-width chronologies in the region (Stahle and Therrel, 1995) and trees at the site. Once tree-rings were crossdated, we assigned fire scars to exact calendar years and, if possible, the season of callus tissue based on the position of the injury within the annual growth ring sequence (Kaye and Swetnam, 1999). Fire scar seasons were classified as either dormant (late fall, winter, early spring), earlywood (spring), latewood (summer, early fall), or undetermined. Fire scar data from individual trees were compiled into a composite event chronology for the study site. FHX2 and FHAES software (Grissino-Mayer, 2001; Brewer et al., 2016) facilitated graphical display and statistical analysis of fire events by time periods.

2.3. Forest demographics and change

Stems of fire-killed trees and shrubs within the fire history study area were sampled within four 3-meter wide belt transects. Transects ran in random directions originating from the geographic center of the fire history study area and ending at the study area boundary (Fig. 1). Within transects, all stems >1.37 m tall were cut at ground level and aged using ring counts to the pith. Tree heights were measured to the nearest decimeter. In cases when trees were partially consumed, heights were estimated to the top of the stem. It is likely that dead trees and small live trees and shrubs (e.g., farkleberry (*Vaccinium arboretum)* and yaupon (*Ilex vomitoria*)) were totally consumed in the BCCF and are not represented in our dataset. A total of 178 stems were aged including loblolly pine, blackjack oak (*Quercus marilandica*), post oak (*Q. stellata*), eastern redcedar (*Juniperus virginiana*), farkleberry, and yaupon. Live seedlings were inspected at ground level and tallied as either resprouts or new germinants.

We supplemented demographic data from transects with the ages of post oak fire history trees and historical satellite imagery. For fire history trees, if the pith was not present on the sample (due to rot), we estimated number of rings to pith by dividing the estimated distance to pith by the average ring-width of the innermost three rings. Due to concern for accuracy for estimating missing rings, we omitted samples from the dataset when the missing distance to pith exceeded 5 cm. We visually compared satellite imagery of the study site for four historical years prior to the BCCF (1938, 1951, 1964, pre-fire 2011) and one-year post-fire (2012). We expected that historical imagery would provide verification for any forest and land use change evidenced by the vegetation data.

2.4. Historical drought

Reconstructed summer season Palmer Drought Severity Index (PDSI; Palmer, 1965; Cook et al., 2004) data were obtained from the National Climate Data Center for grid point 181. Data from this gridpoint is centered on the region of BSP and is based on regional chronologies of post oak, one of the most drought sensitive trees in North America (Stahle and Cleaveland, 1988).

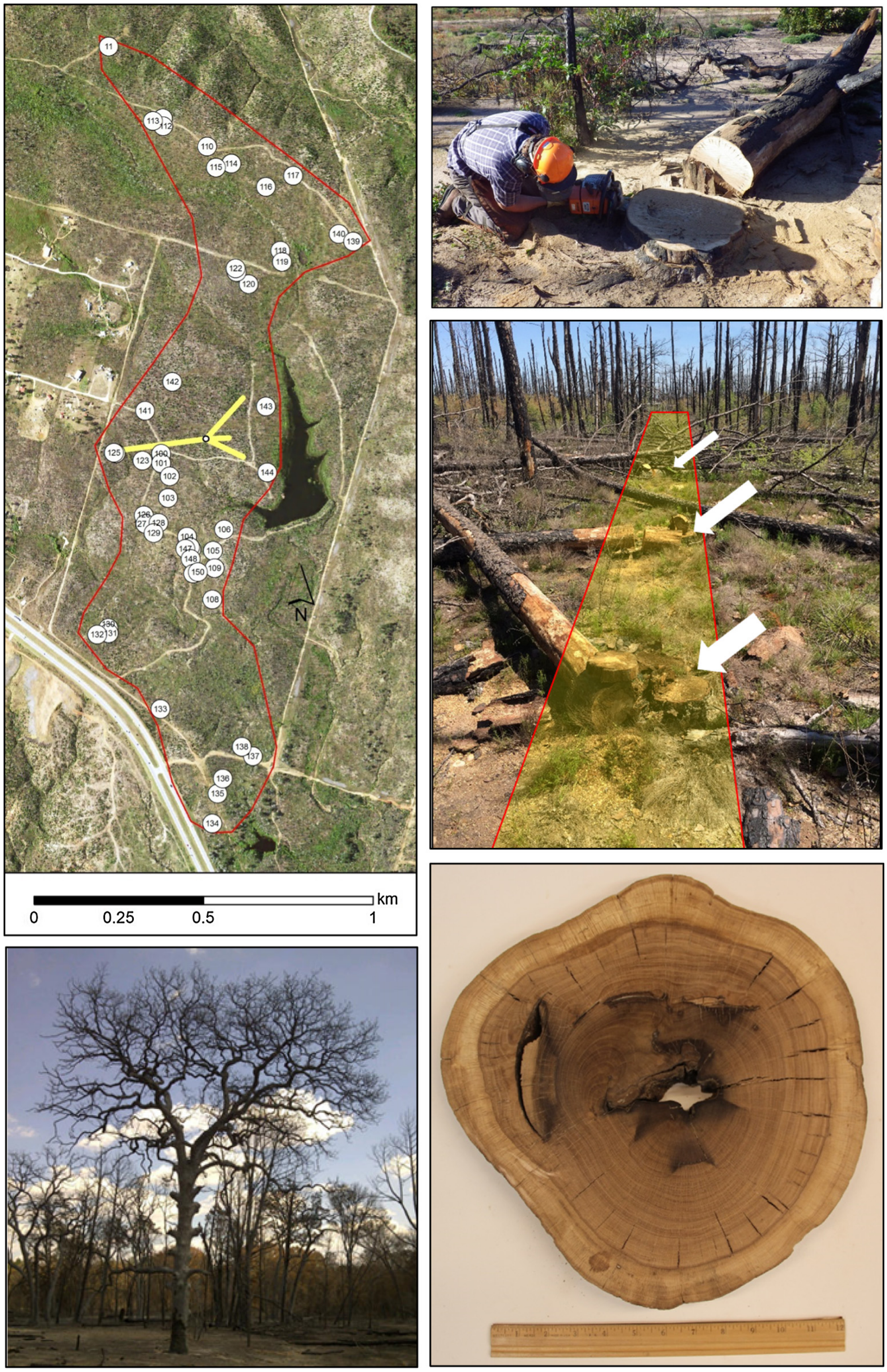

Fig. 1. Top left: Study area (red line) with locations of fire history trees (white circles) and vegetation transects (yellow lines). Tree sample numbers are given inside white circles and correspond to numbers in Fig. 2. Bottom left: Fire killed post oak at study site with branch stubs extending within 3 m of ground, indicating historical open grown growth form. Top right: Worker cuts cross-section at ground level from a fire-killed post oak tree. Middle right: Belt transect through study area utilized to determine pre-fire tree demographics and assess post-fire regeneration. Yellow area indicates belt transect area and white arrows point to the base of trees sampled. Bottom right: Cross-sectional surface of fire-scarred post oak from Bastrop State Park. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.5. Data analysis

Fire intervals (i.e., years between fires) were calculated for individual trees and the study site (i.e., composite of fire scars from all trees). From the composite fire scar data, we calculated ranges of fire intervals, mean fire intervals (MFIs), and Weibull median intervals (WMIs). Fire scars represented the occurrence of fire somewhere in the study area (i.e., because not all fires may have burned the entire study area). Percentages of trees scarred were calculated when at least four trees were recording (1712–2011). From fire event years, we calculated a moving average of fires per decade to portray long-term trends in fire activity. Summary statistics were developed for the full period of record and four sub-periods associated with human and land-use changes: pre-EuroAmerican Settlement period (pre-EAS; 1653–1829), EuroAmerican Settlement period (EAS; 1830–1890), Regional Development period (1891–1940), and Fire Suppression period (1941–2011). The pre-EAS period covered the beginning of the tree-ring record up to the establishment of the nearby Alum Creek community circa 1829. The EAS period included rapid increases in human population and establishment cotton and corn production agriculture and open range grazing (Moore, 1973). The Regional Development period began at the end of open range grazing and included an era of increased mechanized logging, BSP establishment and associated reforestation and facility work by the Civilian Conservation Corps (CCC), National Youth Administration, and Works Progress Administration. The Fire Suppression period included a changing trend in Bastrop County population from declining to rapidly increasing. During this period, BSP resource management and protection has included both fire suppression and, more recently, prescribed burning in some locations.

To test for a historical association between fire occurrence and drought, we conducted a superposed epoch analysis (SEA) of fire events and drought conditions (Fulé et al., 2005). Drought data consisted of the reconstructed PDSI. Data were bootstrapped for 1000 simulated events to derive 95%, 99%, and 99% confidence limits. SEA tests were used to determine whether conditions (wet or dry) during the 6 years preceding and 4 years succeeding fire events were significantly different from average. These tests were conducted for all fire events and then by sub-period. In addition to SEA, we used Pearson correlations to determine whether percentage trees scarred and drought were significantly related. To view long-term trends in drought, we calculated a 7-year moving average of PDSI following the same methods used to calculate fires per decade.

A frequency distribution was developed to depict tree demographics of the forest at the time of the BCCF. For this, numbers of pith (regeneration) dates were plotted by species in 5-year bins. In addition, the frequency of post-fire resprouts and germinants were plotted by species. Height-age relationships were compared between the post oak fire history trees and loblolly pines sampled in transects.

3. Results

3.1. Fire history

The time period covered by the fifty post oak trees sampled for fire history was 1653–2011 (359 years, 10,374 tree rings) (Table 1, Fig. 2). Except for one, all trees had an outer ring date of 2011 suggesting that they were killed in the BCCF (Fig. 2). The average age of fire history trees was 218 years and ranged from 125 to 359. Diameters at breast height of these trees ranged 16.7–65.7 cm with an average of 36.9. The oldest trees were among the oldest post oaks documented in the U.S. (Stahle and Cleaveland, 1988). On many of these trees, live branches and old branch stubs extended near to the ground (Fig. 1), a tree architecture indicative of past open canopy conditions (e.g., savanna or woodland). Based on previous research with post oaks (Stambaugh et al., 2016) and observations during field sampling, several assessments can be made: these trees are among the slowest growing post oaks in the U.S., a high proportion of the post oaks were >200 years old and historically open grown, and many trees encountered and not sampled were hollow, likely due to recurring historical fires. At the study site, few of these older post oak trees resprouted following the BCCF. Due to the general lack of fire for the last 60 years, old injuries (prior to 1951) have had adequate time for wound closure to occur (Smith and Sutherland, 1999; Stambaugh et al., 2017) and no external evidence of past fire scarring was viewable; this is a relatively common condition in long, unburned forests. One exception (sample #BST132), showed to be scarred in 1987 and hollowed out prior to the BCCF; we assume this was likely an isolated fire event (e.g., individual burning tree) based on no scars on other trees, no known fire at BSP, and no evidence that it influenced tree demographics at the site.

A total of 46 fire event years (45 fire intervals) were identified from 98 fire scars (Table 1, Fig. 1). The first and last fire scars recorded were in 1720 and 1987, respectively. Fire intervals on individual trees ranged in length from 1 to 130 years while fire intervals on the composite fire scar chronology (i.e., fire record of site based on all trees) ranged from 1 to 36 years (Table 1). On the composite, the longest fire interval (36 years) was 1951–1987, while many short fire intervals (1–3 years) were concentrated in the period 1885–1940 (Regional Development period). From the early 1700s, the trend in fire frequency increased up to the 1920s, after which fire frequency declined (Fig. 3). The MFI and WMI for the pre-EAS period (1653–1829) were 10.9 and 8.4 years, respectively (Table 1). No fires were recorded from the establishment of the fort Puesta del Colorado in 1804–1821; this was the third longest period without fire and the longest period without fire until the mid-20th century (Fig. 3).

The percentage of trees scarred for all fire years ranged from 2% to 25% with an average of 7.1% (Table 1). In years with earlywood scars ($n = 3$), only 2–3% of trees were scarred, while years with latewood ($n = 13$) and dormant scars ($n = 23$) varied across the full range of percent trees scarred. The majority of latewood scars occurred immediately following EAS up to about 1855. On average, percentages of trees scarred were higher during the pre-EAS period compared to the EAS and Regional Development periods when fires were more frequent (Table 1, Fig. 3). The five years with the highest percentages of trees scarred all occurred in the 18th century (i.e. pre-EAS).

From 1650 to 2003, PDSI ranged from 6.2 (extreme wetness, 1695) to −6.5 (extreme drought, 1925). The frequency distribution of fire events was normally distributed around normal drought conditions (Fig. 4). Percentages of trees scarred during fire years were not correlated with PDSI. For the five fire years with the highest percentages of trees scarred, drought conditions ranged from −0.7 (incipient drought) to 3.0 (very wet). SEA showed that fire event years were not significantly drier or wetter than expected whether the full period or sub-periods were analyzed. Conditions were significantly drier than average three years following fire years during the EuroAmerican Settlement period and five years prior to fires during the Regional Development period, but it is not clear how these lagged conditions are relevant to fire occurrence.

3.2. Forest demographics and change

All but one tree surveyed in belt transects regenerated after 1935 (Fig. 5). Despite post oaks being the oldest trees at the site,

Table 1
Bastrop State Park fire history summary statistics.

	All time	Pre-EuroAmerican settlement	EuroAmerican settlement	Regional development	Fire suppression
Fire chronology					
Calendar years	1653–2011	1653–1829	1830–1890	1891–1940	1941–2011
No. scars	98	19	25	50	4
No. fire years	46	11	12	21	2
Fire intervals					
MFI (yrs)	5.93	10.9	4.9	2.4	na
SD	7.52	9.7	3.6	1.8	na
Interval range (yrs)	1–36	2–27	1–11	1–7	na
WMI (yrs)	3.96	8.4	4.2	2.1	na
Percentage of tree scarred					
Mean	6.4	11.4	5.2	4.8	4
Range	2–25	3–25	2–10	2–10	2–6
Fire seasonality					
% Earlywood fires	7	0	17	5	0
% Latewood fires	26	27	41	19	0
% Dormant fires	50	46	25	67	50
% Undetermined fire	17	27	17	9	50

MFI = Mean fire interval, SD = Standard deviation, WMI = Weibull median interval, na = not applicable.

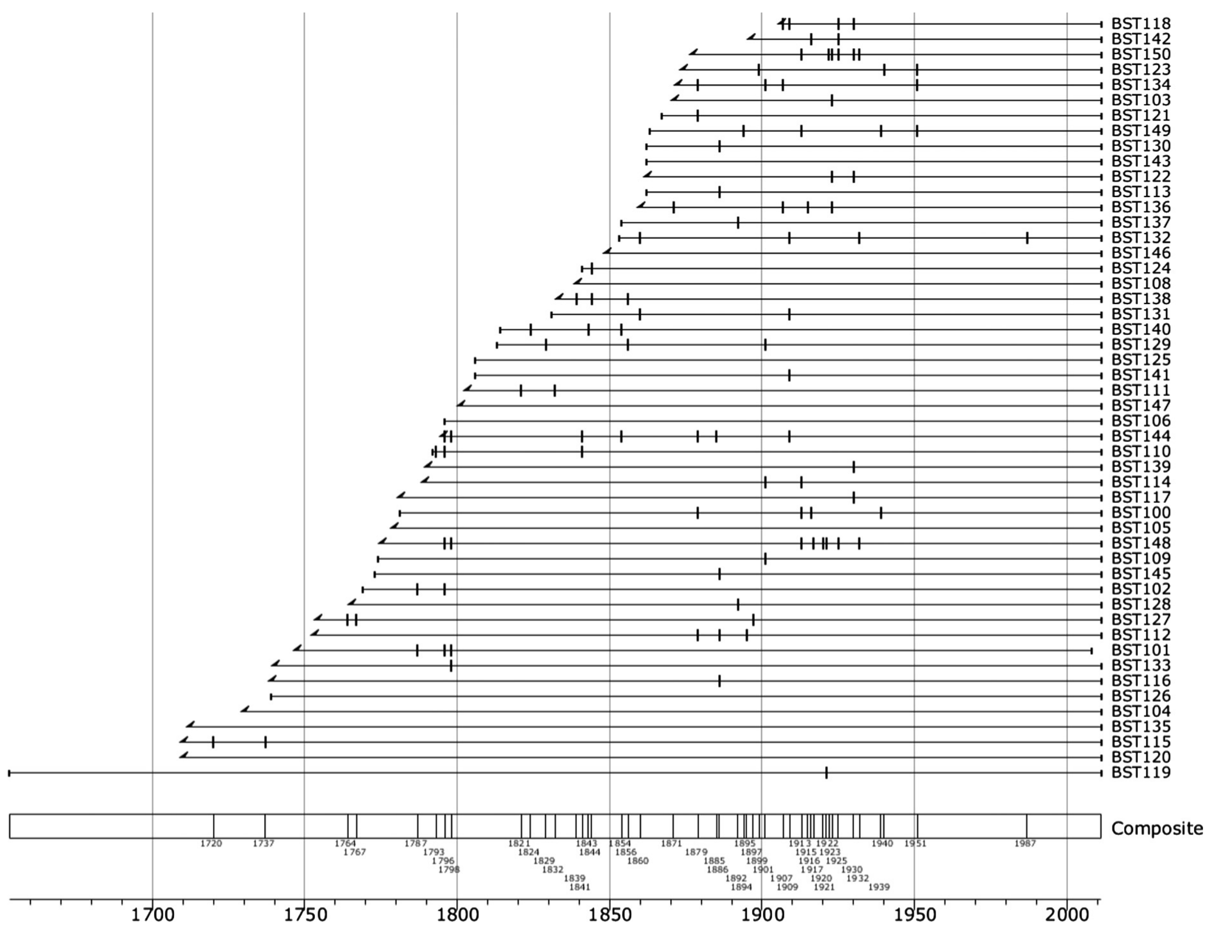

Fig. 2. Fire history chart developed from post oaks at Bastrop State Park. Tree-rings spanned the period 1653–2011. Horizontal lines represent the periods of tree-ring record for individual trees. On the left ends of lines, vertical ends indicate pith years while diagonal ends indicate pith is not present. On the right ends of lines, vertical ends indicate bark years. Bold vertical lines indicate fire scar years. A composite of all fire years at the site is given at the bottom of the chart. Sample numbers (right side) correspond to numbers on topographic map in Fig. 1.

their relative abundance was the lowest. Post-1935 trees occurred in two primary cohorts; one that established circa 1940–1950 and another circa 1965–1975. The 1940–1950 cohort initiated with a relatively high composition of blackjack oak followed by loblolly pine and with small representation of post oak and eastern red-cedar. The peak in regeneration of this cohort occurred circa 1945 after which, overall tree establishment declined until 1960. After 1960, an increase in primarily loblolly pine establishment initiated and continued up to circa 1985. The gradual decline of loblolly pine establishment from 1970 included initiation of farkle-

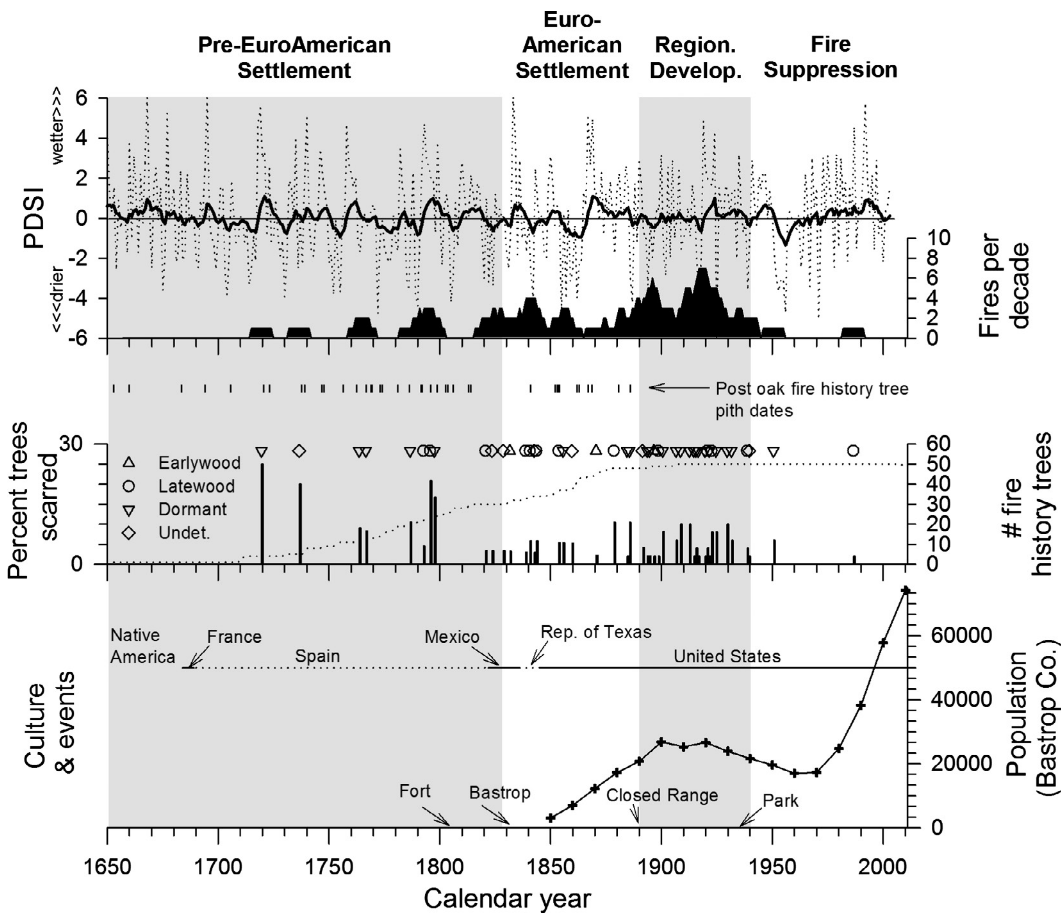

Fig. 3. Timelines depicting changes in drought, fire, trees, and humans during the period 1650–2011. Decadal population data of Bastrop County were retrieved from the U.S. Census Bureau (2015) for the period of 1850–2010.

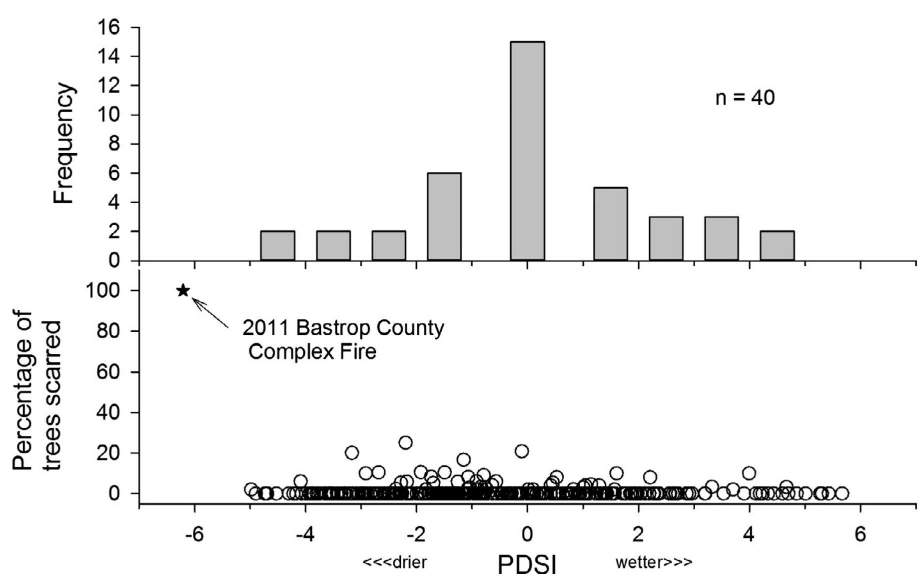

Fig. 4. Top: Frequency distribution of 40 historical fire events stratified by drought condition. Bottom: Percentages of trees scarred in historical fire year plotted by drought condition. Drought condition of 2011 shown in top left.

berry, some which were 35+ years old at the time of the BCCF. All regeneration surveyed in 2014 (i.e., following the BCCF) had initiated from resprouting individuals with blackjack oak representing over 95% of tree regeneration. No loblolly pine regeneration was observed, despite its pre-fire dominance.

Sharp contrast existed between the height growth of post oaks and loblolly pine (Fig. 6). Loblolly pines had much faster height

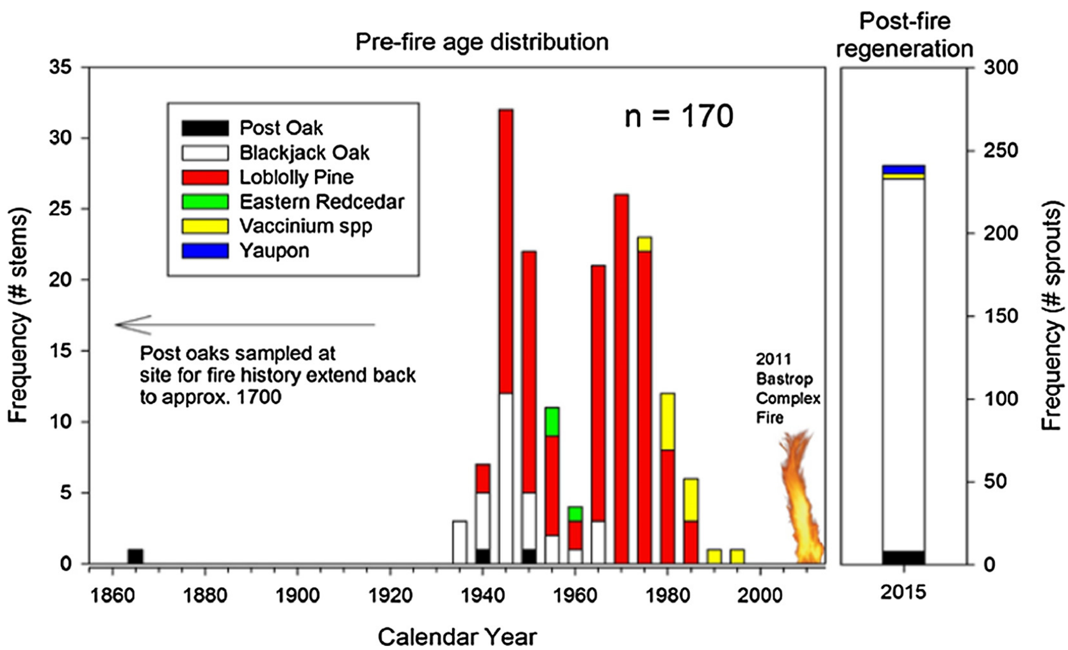

Fig. 5. Age distribution of stems >1.37 m tall sampled in 4, 3-meter wide belt transects. Transects radiated from the center to the edge of the study area. Yaupon (*Ilex vomitoria*) could not be aged due to undiscernible ring boundaries. Frequency of young/small stems (following year 2000) may be underrepresented due the effects of the 2011 Bastrop County Complex Fire. Generally, the pre-fire Yaupon age distribution is expected to be comparable to *Vaccinium* spp., but with higher frequency that increases with time. Basal sprouting was the only post-fire regeneration observed of woody vegetation within transects.

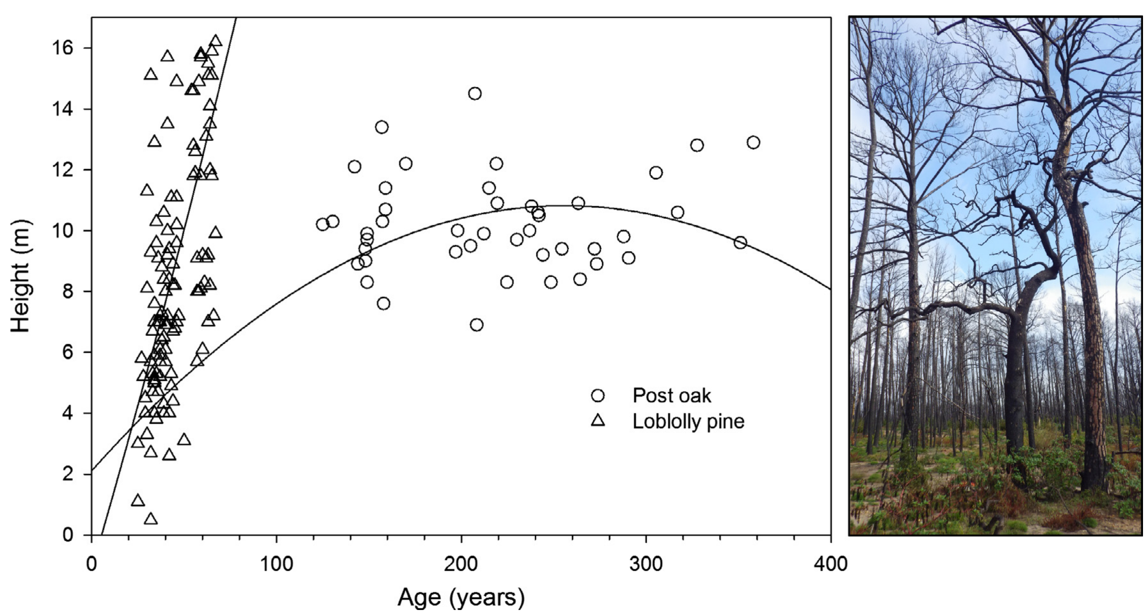

Fig. 6. Left: Scatterplot of post oak (*Quercus stellata, Q. margaretta*) and loblolly pine (*Pinus taeda*) height growth with regression lines shown to compare height growth trends. Right: Loblolly pine, regenerating since the 1940s, developed a super canopy above post much older oaks. Post oak is the shorter, larger diameter tree in middle of photo with all other trees being loblolly pine.

growth and ability to reach greater overall heights, despite the two species likely have comparable rates up to age 20. As early as 30 years, loblolly pine attained the maximum height observed for post oaks at 200 years. Mean height of the 100–350+ yr old post oaks was 10.1 m. Although maximum heights may not have been observed for loblolly pines (i.e., since they were killed in BCCF at maximum ages of 67 years), the mean height of mature trees is likely 4 to 6 meters taller than post oaks, effectively occupying a super canopy position.

Aerial imagery and tree ages show complementary evidence of increased forest density and decreased canopy cover since the mid-20th century (Fig. 7). Evidence of increased tree density initiating in mid-1940 s from tree aging was supported by aerial imagery showing decreasing open space from 1938 to 1951. In the 1951 image, the major cohort of loblolly pine would have been about 10 years old or less. Imagery showed canopy openness decreasing and by the time of the 1964 image, most of the open canopy space appeared to have been filled. Though not viewed through imagery, further canopy closure must have occurred due to the loblolly

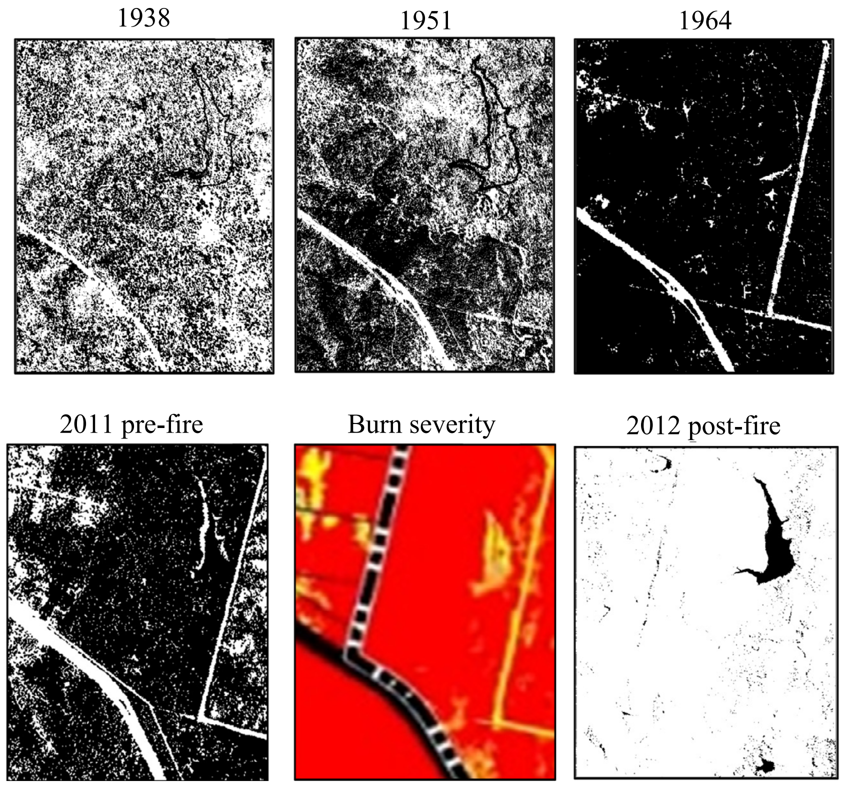

Fig. 7. Black and white conversion of aerial photography of southern half of study area showing forest densification (black = forest, white = non-forest) through the 20th century up to 2011 and then in 2012. Burn severity map of Sept. 2011 Bastrop County Complex Fire shows areas heavily burned (red), moderately burned (orange), and lightly burned (yellow). Black polygon in 2012 scene indicates Harmon Lake and its area is outlined in 1938 and 1951scenes.

pine-dominated cohort of trees circa 1960–1975. Based on the imagery, it is not possible to discern the relative composition of deciduous versus evergreen foliage (trees).

4. Discussion

4.1. Fire history

Post oak trees at BSP revealed one of the longest histories of fire in the southcentral U.S. to date. East of the Great Plains, this is the southernmost fire scar history study developed from oaks. Aside from the last half century, fires were relatively frequent, low severity, and dominated by dormant and summer / early fall season events. Compared to sites in Oklahoma and northern Texas (Clark et al., 2007; DeSantis et al., 2010b; Allen and Palmer, 2011; Stambaugh et al., 2011, 2016), BSP had less frequent fire on average in the pre-EAS period when most other sites had MFIs ranging from 3 to 7 years. Based on previous work through modeling and vegetation analyses, historical fire intervals in this area were estimated to have ranged from 1 to 6 years (Stambaugh et al., 2014). The finding of a longer pre-EAS MFI is somewhat unexpected since the site is located farther south where fire seasons are potentially longer and climate conditions are conducive to supporting more frequent fire (Guyette et al., 2012). A longer fire season or warmer-drier, and potentially longer growing season, may explain why more late-growing season fires were observed at the study site than has been documented by any other post oak studies to date.

Over the last three centuries, fires occurred across a range of drought conditions. Drought was not significantly related to fire occurrence or severity. Often, drought influences on fire regimes are not manifested without multiple sites across larger landscapes (Stambaugh et al., 2014). Overall, percentages of trees scarred were low compared to other sites in the eastern U.S. (Stambaugh et al., 2016). Considering the historical drought conditions (Cook et al., 2004), the BCCF occurred during the 4th driest summer since the year 996; the summer of 2009 was 3rd driest. For the 46 fire years since 1653, only the summer of 1925 was drier than 2011.

Fire regimes that have fire years primarily in drought conditions are hypothesized to be more climate controlled, while fire regimes that have fire years in wet years are more anthropogenic controlled (Muzika et al., 2015). From this framework and based on our results, it would appear that the fire regime during the last three centuries was strongly controlled by human influences (e.g., ignitions). Certainly many different human influences were possible since this region transferred from Native American (pre-1684), to French (1684–1689), to Spanish (1690–1821), to Mexican (1821–1836), to the Republic of Texas (sovereign nation; 1836–1845), and then to the United States (1845 – present). At the time of European exploration, this area was inhabited by the Tonkawa Indians, a tribe associated with the Cross Timbers ecoregion whose population is believed to have been displaced to central Texas from Oklahoma and dramatically reduced in number due to introduced diseases and war (Hasskarl, 1962; Schilz, 1983). According to Willbarger (2015), through the early 19th century, Bastrop County suffered from more Native American conflicts than any other in Texas with recurring battles being fought between Anglos and the Comanche with the Tonkawa siding with the former (Moore, 2007).

In 1804, a Spanish fort (Puesta del Colorado) existed 6 km east of the study site at the present town of Bastrop. Located approximately 6 km to the south of the study site, near the junction of the Colorado River and Alum Creek, the community of Alum Creek was established circa 1829. During the next decade, churches, schools, and sawmills were constructed near the fort and Alum

Creek community (Bastrop Historical Society, 1955). The town of Bastrop was established in 1832 at a crossing of the Colorado River that had had been important to a network of trails traveled by bison, Native Americans, and Spanish explorers. In the late 17th century, these trails had become El Camino Real de los Tejas (i.e., The San Antonio Road), the most important route connecting San Antonio, Texas with Natchitoches, Louisiana, the earliest settlement in Louisiana (Burton and Smith, 2008). El Camino Real supported east Texas missions by allowing transport of freight and supplies (Handbook of Texas).

Within 4 km of the study site, El Camino Real de los Tejas passed through the ecological transition between Blackland Prairie, Oak Woodlands, and the Lost Pines, an approximately 34,400 ha portion of the loblolly pine range that is disjunct from the primary range in the East Texas Piney Woods (Bryant, 1977; LBJ School of Public Affairs, 1998; Al-Rabah'ah and Williams, 2004). The 2700-hectare area of BSP is unique in that it is the western edge of the Lost Pines forest region. As the westernmost pine trees in eastern Texas, logs from these trees were sought from the mid-18th to early 19th centuries for the construction of buildings in Bastrop, Austin, San Antonio, and northern Mexico (source: Bastrop State Park history webpage; http://tpwd.texas.gov/state-parks/bastrop/park_history). A long history of pine resource use (Moore, 1973) likely resulted in increases and decreases in the local importance of loblolly pine through time. Lost Pines lumbering reached its peak in the 1840s, but continued for decades until the resource became limited (Texas Handbook).

Although direct attribution of human causes of past fires at BSP are not possible, human-caused fires were reported as early as 1529 in Texas (Lehmann, 1965) and the 1870s in Bastrop County (Zelade, 2012). The timing of past changes in fire frequency almost surely reflects changes in human occupations, cultures, and land uses as has been the case across the U.S. Some notable human and fire changes were: decreased fire after establishment of fort Puesta del Colorado, decreased fire during open range grazing and increased fire beginning with closed range, and decreased fire during the 20th century with known fire protection.

Across the U.S., establishment of forts coincided with various human land use changes that affected fire regimes. These ranged from increased conflict and warring to increased property protection and fire suppression. For example, establishment of Fort Leavenworth in Kansas coincided with two decades of increased fire frequency along the Missouri River loess hills (Stambaugh et al., 2006). The establishment of Fort Sill in Oklahoma coincided with a period of high fire frequency, including occurrences of annual burning (Stambaugh et al., 2014). The association between fire frequency and fort establishment at Bastrop was generally opposite of this trend, with fire frequency decreasing during and in the decades following establishment. Further, comparison between temporal changes in fire frequency at the study site and another site near Natchitoches, Louisiana (the eastern terminus of El Camino Real) are nearly opposite (Stambaugh et al., 2011) suggesting that the cultural fire use, including the impactful period of the Louisiana Purchase, did not influence the fire regime at BSP.

In addition to ignitions, across the Great Plains and the western U.S. in particular, historical human influence via animal grazing affected fire regimes through fuel reduction (i.e., animal consumption), fuel discontinuity, and increased fire suppression efforts to protect forage (Madany and West, 1983; Touchan et al., 1995; Courtwright, 2007; Taylor et al., 2016). From an extensive fire history dataset across eastern Oregon and Washington, Heyerdahl et al., (2001), concluded that declines in fire occurrence and size during the late 1800s were caused by a combination of above-average precipitation and grazing. Fire-climate-grazing interactions also existed in Texas, and may be evidenced in the fire scar record. In Bastrop County, cattle numbers quadrupled from 1850 to 1860 reaching 40,000 individuals. It is plausible that the observed decreases in fire from the 1860s to the mid-1880s is attributable to grazing of fine fuels. Decreased fire occurrence was also observed during this era at Purtis Creek State Park, located approximately 270 km north of BSP (Stambaugh et al., 2011). From 1866 to 1885, 5.7 million cattle were driven from Texas to pastures in the northern Great Plains (Mattison, 1951). Interestingly, fire occurrences began to increase at BSP around 1885 to 1890; a change coincident with the severe 1886–87 winter that killed high percentages of cattle in the northern Great Plains and essentially ended open range grazing by 1890 (Mattison, 1951).

Throughout the U.S., many changes in land use practices, human populations and cultures correspond with changes in fire regimes. These changes infer strong human control on ignitions and fire spread. In many cases, grazing / human effects on fire regimes have the ability to mask the climate influences on fire occurrences. To date, relatively little work has been done to understand historical fire-human-climate-livestock interrelationships in Texas, despite their known present day linkages and relevance to emerging rangeland management practices and issues (e.g., patch-burn grazing (Fuhlendorf and Engle, 2004), prescribed burning (Twidwell et al., 2013). Consequently, without more spatial replication of study sites in Texas, we lack the ability to place the BSP fire history in a broader regional framework (e.g., including Edwards Plateau, South Texas Brush Country, Piney Woods) that characterizes the changing, yet coupled, human-environmental system.

The nearest landscapes with multiple fire history sites and comparable vegetation are located in the Wichita Mountains of Oklahoma (Stambaugh et al., 2014) and Ozark Highlands of Oklahoma, Arkansas, and Missouri. In the Wichita Mountains, fire frequency response during EAS was different in that it dramatically increased in the mid-to late-1800s. High fire frequency corresponded to reduced fire severity and tree cohorts initiated during prolonged fire-free periods. In the Ozarks, fire frequency increased with eastern Native American immigration and EAS. Here, Guyette et al. (2002) showed clear fire regime stages associated with changing human cultures, their populations and land uses; these stages have been models for fire regimes elsewhere. In the Ozarks, fire frequency increased coincident with EAS due, in large part, due to efforts to reduce woody vegetation and promote forage for livestock. We hypothesize that the effect of early EuroAmerican settlers on fire frequency differed between closed canopy forests with leaf litter fuels and open forests (e.g., savannas and woodlands) with grass fuels. In less forested areas that were initially grass-dominated, forage would have been readily available upon arrival, and the immediate human influence on the fire regime would be decreased frequency due to either grazing (fine-fuel consumption) or fire suppression (forage and livestock protection).

4.2. Historical vegetation transitions

Based on the post oak tree ages and architectures, the forest canopy structure was open during at least a portion of the period from 1650 to 1800. Loblolly pines (50–70 yrs old) were a dominant component of the site at the time of the BCCF forming a super canopy that burned with crown fire. Before the 1940s, it is difficult to determine the importance of loblolly pine at the site. It could not have been a high density component of the site or super canopy when post oak trees formed open grown architectures. Scattered older loblolly pines (e.g., up to 140 years) exist at the study site and in other locations of BSP. However, considering its characteristic as a relatively fire-intolerant tree species and the frequent fire that occurred from the 1890s to 1940s, loblolly pine was likely less dominant. Under longer-term periods (e.g., centuries) with recurring fires, loblolly pine would be expected to have persisted in sites where fire frequency or intensity was lowered (e.g., wet sites, topographically rough terrain). The 1940s loblolly pine cohort corresponded with a significant decrease in fire occurrence along with other human activities. Though not known, loblolly pine plantings in the 1940s may have been the source of this regeneration since tree plantings were documented for other portions of BSP during this time.

Within the extent of this study area and time period, there is no indication that high severity, stand-replacing fires preceded the BCCF back to at least 1650. Due to the high severity effects of the BCCF, the site is currently dominated by blackjack oak, with little post oak, and no loblolly pine regeneration (although replantings of loblolly pine have occurred since our sampling). The dominance of blackjack oak is verified across larger extents of the BCCF (Keith and Booth, 2013) but, without disturbance (e.g., recurring fire), will likely succeed to a forest composed of potentially larger, and taller species. As a consequence of past disturbance and land uses, the post oak community was generally dominated by older and likely senescing trees (i.e., many trees were at or approaching maximum longevity) at the time of the BCCF. This condition was likely a significant limiting factor to its post-fire success, since probability of resprouting generally declines with age and ceases at very mature ages.

4.3. Conclusions

The changing vegetation dynamics at BSP over the last 300 years raises many questions about past interactions among oaks, pines, fire, and humans. Documenting the historical vegetation and fire ecology has important implications for identifying potential causes of change and the precedence for the conditions associated with the BCCF. The long presence of oak and evidence for historically open canopy conditions were surprising findings and in sharp contrast with vegetation conditions at the time of the BCCF. Based on the fire history record, prior to the BCCF, fire activity had been lower than at any time since at least 1720. Due to this, and likley other contributing land uses, the site had a high density of trees of primarily post-1940 origin. In summary, it is possible that the vegetation conditions at the study site during the BCCF were unprecedented in our record. The past role of logging, particularly of loblolly pine, remains unclear and obscures understanding past fire and vegetation dynamics. Additional comparable data (i.e., fire history, tree growth and cohorts, documentary) from other sites in the oak woodlands and Lost Pines ecotone could help to overcome this by determining the scale and timing of past human land uses and historical to modern fire-vegetation transitions. Further, supplementary data (e.g., plot data) on loblolly pine and oak survival through repeated burning would further inform the historical record and could make significant contributions towards understanding the applied historical ecology of BSP's Lost Pines and Oak Woodlands transitional region.

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References

Allen, M.S., Palmer, M.W., 2011. Fire history of a prairie/forest boundary: more than 250 years of frequent fire in a North American tallgrass prairie. J. Veg. Sci. 22, 436–444.
Al-Rabah'ah, M.A., Williams, C.G., 2004. An ancient bottleneck in the Lost Pines of central Texas. Mol. Ecol. 13, 1075–1084.
Ansley, R.J., Wu, X.B., Kramp, B.A., 2001. Observation: long-term increases in mesquite canopy cover in a North Texas savanna. J. Range. Manage. 54, 171–176.
Bastrop Historical Society, 1955. In the Shadow of the Lost Pines; a History of Bastrop County and Its People. Bastrop Advertiser, Bastrop, TX. 44p.
Brewer, P.W., Velásquez, M.E., Sutherland, E.K., Falk, D.A., 2016. Fire History Analysis and Exploration System (FHAES) version 2.0.1 [computer software] <http://www.fhaes.org>. http://dx.doi.org/10.5281/zenodo.34142.
Bryant Jr., V.M., 1977. A 16,000 year pollen record of vegetational change in central Texas. Palynology 1 (1), 143–156.
Brown, D.J., Duarte, A., Mali, I., Jones, M.C., Forstner, M.R.J., 2014. Potential impacts of a high severity wildfire on abundance, movement, and diversity of herpetofauna in the Lost Pines ecoregion of Texas. Herpetolog. Conserv. Bio. 9, 192–205.
Burton, H.S., Smith, F.T., 2008. Colonial Natchitoches: A Creole Community on the Louisiana-Texas Frontier. Texas A & M University Press, College Station, TX, US.
Cathey, J.C., Mitchell, R., Dabbert, B., Prochaska, D.F., DuPree, S., Sosebee, R., 2006. Managing yaupon in the post oak savanna. Rangeland 28, 24–27.
Clark, S.L., Hallgren, S.W., Engle, D.M., Stahle, D.W., 2007. The historic fire regime on the edge of the prairie: a case study from the Cross Timbers of Oklahoma. In: Proceedings of the Tall Timbers Fire Ecol. Conf., vol. 23, pp. 40–49.
Cook, E.R., Meko, D.M., Stahle, D.W. & Cleaveland, M.K. 2004. North American summer PDSI reconstructions. World Data Center for Paleoclimatology Data Contribution Series #2004-045. Available at: <http://www.ncdc.noaa.gov/paleo/newpdsi.html>. Accessed 10 October 2016.
Courtwright, J.R., 2007. Taming the red buffalo: prairie fire on the Great Plains. PhD Diss., Univ. Arkansas, 266 p.
DeSantis, R.D., Hallgren, S.W., Palmer, M.W., Lynch, T.B., Burton, J.A., 2010a. Long-term directional changes in the upland oak forests of Oklahoma, USA. J. Veg. Sci. 21, 606–615.
DeSantis, R.D., Hallgren, S.W., Stahle, D.W., 2010b. Historic fire regime of an upland oak forest in south-central North America. Fire Ecol. 6, 45–61.
Engle, D.M., Coppedge, B.R., Fuhlendorf, S.D., 2007. From the dust bowl to the Great Green Glacier: human activity and environmental change in Great Plains grasslands. In: Van Auken, O.W. (Ed.), Western North American Juniperus Communities – A Dynamic Vegetation Type. Springer.
Fuhlendorf, S.D., Engle, D.M., 2004. Application of the fire-grazing interaction to restore a shifting mosaic on tallgrass prairie. J. Appl. Ecol. 41, 604–614.
Fulé, P.Z., Villanueva-Diaz, J., Ramos-Gomez, M., 2005. Fire regime in a conservation reserve in Chihuahua, Mexico. Can. J. For. Res. 35, 320–330.
Grissino-Mayer, H.D., 2001. FHX2-software for analyzing temporal and spatial patterns in fire regimes from tree rings. Tree-Ring Res. 57, 115–124.
Guyette, R.P., Muzika, R.M., Dey, D.C., 2002. Dynamics of an anthropogenic fire regime. Ecosystems 5, 472–486.
Guyette, R.P., Stambaugh, M.C., 2004. Post oak fire scars as a function of diameter, growth, and tree age. For. Ecol. Manage. 198, 183–192.
Guyette, R.P., Stambaugh, M.C., Dey, D.C., Muzika, R.-M., 2012. Predicting fire frequency with chemistry and climate. Ecosystems 15, 322–335.
Hanberry, B.B., Kabrick, J.M., He, H.S., 2014. Densification and state transition across the Missouri Ozarks landscape. Ecosystems 17, 66–81.
Hann, W., Shlisky, A., Havlina, D., Schon, K., Barrett, S., DeMeo, T., Pohl, K., Menakis, J., Hamilton, D., Jones, J., Levesque, M., Frame, C., 2004. Interagency Fire Regime Condition Class Guidebook. Last update January 2008: Version 1.3.0 [Homepage of the Interagency and The Nature Conservancy fire regime condition class website, USDA Forest Service, US Department of the Interior, The Nature Conservancy, and Systems for Environmental Management]. Available: <www.frcc.gov>.
Hardy, C.C., Schmidt, K.M., Menakis, J.M., Samson, N.R., 2001. Spatial data for national fire planning and fuel management. Int. J. Wildland Fire 10, 353–372.
Hasskarl Jr., R.A., 1962. The culture and history of the Tonkawa Indians. Plains Anthropolog. 7, 217–231.
Heyerdahl, E.K., Brubaker, L.B., Agee, J.K., 2001. Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. Ecology 82, 660–678.
Kaye, M.W., Swetnam, T.W., 1999. An assessment of fire, climate, and Apache history in the Sacramento Mountains, New Mexico, USA. Phys. Geogr. 20, 305–330.
Keith, E.L., Booth, E., 2013. Vegetation assessment following Bastrop County Complex Fire using thirty-two fire monitoring handbook (FMH) vegetation plots at Bastrop State Park, Bastrop County, TX. Final report to the Texas Parks and Wildlife Department. 15 p.
Keith, E.L., Creacy, G., 2011. Bastrop State Park post-fire vegetation assessment following the 2011 Bastrop County Complex Wildfire. Report to the Texas Parks and Wildlife Department. 26 pp.
Lehmann, V.W., 1965. Fire in the range of Attwater's prairie chicken. Proceedings of the Tall Timbers Fire Ecology Conference 4, 127–142.
Madany, M.H., West, N.E., 1983. Livestock grazing-fire regime interactions with montane forests of Zion Naitonal Park, Utah. Ecology 64, 661–667.
Mattison, R.H., 1951. The hard winter and the range cattle business. Montana Mag. History 1, 5–21.
Moore, B., 1973. Bastrop County, 1691–1900. Educator Books. 327 p.
Moore, W.E., 2007. An archeological survey for the Lost Pines Trail Project in central Bastrop County, Texas. A report prepared for Bastrop County Water Control and Improvement District #2. 20 p.

Muzika, R.-M., Guyette, R.P., Stambaugh, M.C., Marschall, J.M., 2015. Fire, drought, and humans in a heterogeneous Lake Superior landscape. J. Sustain. For. 34, 49–70.

Nowacki, G.J., Abrams, M.D., 2008. The demise of fire and 'mesophication' of forests in the eastern United States. Bioscience 58, 123–138.

Nowacki, G.J., Abrams, M.D., 2015. Is climate an important driver of post-European vegetation change in the Eastern United States? Glob. Change Biol. 21, 314–334.

NCDC (National Climate Date Center), 1994. Time bias corrected divisional temperature-precipitation-drought index. Documentation for dataset TD-9640. Available from DBMB, NCDC, NOAA, Federal Building, 37 Battery Park Ave. Asheville, NC 28801-2733, 12 pp.

Palmer, W.C., 1965. Meteorological drought. Research Paper No. 45, U.S. Weather Bureau, Washington DC. 58 p.

Rissel, S., Ridenour, K., 2013. Ember production during the Bastrop Complex Fire. Fire Manage. Today 72, 7–13.

Ryan, K.C., Knapp, E.E., Varner, J.M., 2013. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. Frontiers in Ecol. Environ. 11, e15–124.

Schilz, T.F., 1983. People of the Cross Timbers: A History of the Tonkawa Indians. Texas Christian University, Ft. Worth. 456 p.

Smeins, F.E., Fuhlendorf, S.D., Taylor Jr., C.A., 2005. History and use of fire in Texas. In: Rollins, D. (Ed.), Fire as a Tool for Managing Wildlife Habitat in Texas. Texas Cooperative Extension, San Angelo, Texas, USA, pp. 6–16.

Smith, K.T., Sutherland, E.K., 1999. Fire-scar formation and compartmentalization in oak. Can. J. For. Res. 29, 166–171.

Stahle, D.W., Cleaveland, M.K., 1988. Texas drought history reconstructed and analyzed from 1698 to 1980. J. Climate 1, 59–74.

Stahle, D.W., Therrel, M.D., 1995. South Texas composite, post oak ring-width data. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # TX049. NOAA/NCDC Paleoclimatology Program, Boulder CO, USA.

Stambaugh, M.C., Guyette, R.P., McMurry, E.R., Dey, D.C., 2006. Fire history at the eastern Great Plains margin, Missouri River loess hills. Great Plains Res. 16, 149–159.

Stambaugh, M.C., Guyette, R.P., Marschall, J.M., Dey, D.C., 2016. Scale dependence of oak woodland historical fire intervals: contrasting The Barrens of Tennessee and Cross Timbers of Oklahoma, USA. Fire Ecol. 12, 65–84.

Stambaugh, M.C., Smith, K.T., Dey, D.C., 2017. Fire scar growth and closure rates in white oak (Quercus alba) and the implications for prescribed burning. For. Ecol. Manage. 391, 396–403.

Stambaugh, M.C., Sparks, J.C., Abadir, E.R., 2014. Historical pyrogeography of Texas. Fire Ecol. 10, 72–89.

Stambaugh, M.C., Sparks, J., Guyette, R.P., Willson, G., 2011. Fire history of a relict oak woodland in northeast Texas. Range. Ecol. Manage. 64, 419–423.

Stokes, M.A., Smiley, T.L. 1968. Introduction to tree-ring dating. University of Chicago Press. 73 pp.

Swetnam, T.W., Allen, C.D., Betancourt, J.L., 1999. Applied historical ecology: using the past to manage for the future. Ecol. Applic. 9, 1189–1206.

Taylor, A.H., Trouet, V., Skinner, C.N., Stephens, S. 2016. Socioecological transitions trigger fire regime shifts and modulate fire-climate interactions in the Sierra Nevada, USA, 1600–2015 CE.

Texas A & M Forest Service, 2012. 2011 Texas wildfires: common denominators of home destruction. 48 p.

Texas Handbook. Available online: <https://tshaonline.org/handbook/online/articles/hcb03>.

Touchan, R., Swetnam, T.W., Grissino-Mayer, H.D., 1995. Effects of livestock grazing on pre-settlement fire regimes in New Mexico. Pages 268-272 in J.K. Brown, R. W. Mutch, C.W. Spoon, R.H. Wakimoto (Eds.) Symposium of Fire in Wilderness and Park Management. USDA Forest Service GTR INT 320.

Twidwell, D., Rogers, W.E., Fuhlendorf, S.D., Wonkka, C.L., Engle, D.M., Weir, J.M., Kreuter, U.P., Taylor Jr., C.A., 2013. The rising Great Plains fire campaign: citizens' response to woody plant encroachment. Front. Ecol. Environ. 11, e64–e71.

Willbarger, J.W., 2015. Indian depredations in Texas. CreateSpace Independent Publishing Platform. 424 p.

Zelade, R., 2012. A History of the State Fire Marshal's Office: 1910–2011. Texas Department of Insurance, Austin, Texas, p. 94.