Research Article

Scale Dependence of Oak Woodland Historical Fire Intervals: Contrasting The Barrens of Tennessee and Cross Timbers of Oklahoma, USA

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ABSTRACT

Characterization of scale dependence of fire intervals could inform interpretations of fire history and improve fire prescriptions that aim to mimic historical fire regime conditions. We quantified the temporal variability in fire regimes and described the spatial dependence of fire intervals through the analysis of multi-century fire scar records (8 study sites, 332 trees, 843 fire scars) derived from two historically post oak (*Quercus stellata* Wangenh.) woodland landscapes. Despite large differences in fire environment conditions, study sites (~1 km^2) burned frequently (mean fire interval [MFI] ≤10 yr) before Euro-American settlement (pre-EAS), with sites in Tennessee showing higher overall fire frequency than sites in Oklahoma, USA. Pre-EAS MFIs decreased exponentially with increasing spatial extent from individual trees (~1 m^2) to landscapes (~100 km^2). The relationship between MFI and spatial extent may help to explain how historical observations of annual burning could be recorded in woodlands, when experimental studies suggest that this is too frequent for

RESUMEN

La caracterización de la dependencia de la escala de los intervalos de fuego podría informar sobre interpretaciones de la historia del fuego y mejorar prescripciones que apunten a imitar condiciones históricas del régimen de incendios. Nosotros cuantificamos la variabilidad temporal en los regímenes de fuego y describimos la dependencia espacial de intervalos de fuego a través del análisis de archivos de cicatrices de fuego por muchas centurias (8 sitios de estudio, 332 árboles, 843 cicatrices de fuego) derivados de dos paisajes históricos de arbustales de roble de los postes (*Quercus stellata* Wangenh). A pesar de las grandes diferencias en las condiciones ambientales de fuego, los sitios de estudio (~1 km^2) se quemaron frecuentemente (intervalo promedio de fuego [MFI] ≤ 10 años) antes del asentamiento euro-americano (pre-EAS), mostrando una frecuencia general de fuegos en los sitios de Tennessee más alta que en los de Oklahoma, EEUU. Los MFIs en el pre-EAS decreció en forma exponencial con el grado de aumento espacial desde árboles individuales (~1 m^2) hasta paisajes (~100 km^2). La relación entre en MFI y la extensión espacial puede ayudar a explicar como observaciones históricas de quemas anuales podrían ser recopiladas en arbustales, cuando estudios experimentales sugieren que tree recruitment. Further investigations of spatial dependence of fire intervals would improve our ability to relate historical and experimental fire data to present day fire prescriptions, and vice versa.

esto es muy frecuente para el reclutamiento de árboles. Otras investigaciones de la dependencia espacial de los intervalos de fuego podrían mejorar nuestra habilidad para relacionar datos históricos y experimentales de fuego a prescripciones actuales de fuego y vice versa.

Keywords: management, oak woodland**,** pyrodiversity, restoration, spatial extent, succession

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INTRODUCTION

Nineteenth- to twentieth-century trends of oak (*Quercus* spp. L.) woodland communities in the eastern US overwhelmingly show transition to more closed-canopy conditions and fire-intolerant tree species (Dyer 2001, Nowacki and Abrams 2008, Hanberry *et al*. 2014). Prior to Euro-American settlement (pre-EAS) and logging effects, fire was considered the primary disturbance that maintained oak woodland communities. Interest in woodland restoration and management is increasing, not only because of historical prevalence and modern rarity, but also due to the multiple ecological benefits resulting from fire restoration compared to fire suppression. Recently, research has focused on how fire treatments may be incorporated into silvicultural systems (Ryan *et al*. 2013, Brose 2014, Dey and Kabrick 2015). Detailed and spatially explicit information is needed about the fire ecology of woodlands, including how species and ecosystem function respond to specific fire regime conditions, and how or if tree recruitment can be sustained through repeated, long-term burning. Specifically, understanding the scale dependencies of fire intervals would improve the ability to crosswalk between sources that characterize woodlands such as historical data, experimental data, and present day fire monitoring. Additionally, quantifying the variability in fire intervals across spatial and temporal scales may inform us about their relative importance as related to oak woodland development.

Oak woodlands are highly variable forest communities with open canopies ranging from 30 % to 100 % closure; sparse midstories; and a dense ground flora rich in forbs, grasses, and sedges (Nelson 2005). Historically, woodlands existed in ecoregions throughout the Eastern deciduous forest (Braun 1950, Bailey 1997), including being embedded components of glades, barrens, and oak-pine ecosystems, accompanying shortleaf pine (*Pinus echinata* Mill.), longleaf pine (*P. palustris* Mill.), red pine (*P. resinosa* Aiton), and pitch pine (*P. rigida* Mill.). Mature canopy heights may range from 6 m to 27 m depending on site conditions. Nelson (2005) identified 18 different oak woodland communities in Missouri, USA, and vascular plant species richness can exceed 200 species ha^{-1}. Diverse species compositions and open canopy structures of woodlands are attributed to repeated and relatively frequent fires (Olmstead 1857, Swallow 1859), although effects of other interacting disturbances and drought also promote canopy openness (McEwan *et al*. 2011). Oak woodlands with these characteristics occurred throughout North America pre-EAS despite being relatively rare today (Hanberry *et al*. 2014). During the twentieth century to the present, rates of forest transitions from open- to closed-canopy conditions have varied by region and species assemblages (Guyette *et al*.

2003, DeSantis *et al*. 2011, Cocking *et al*. 2012, Stambaugh *et al*. 2014*a*). In long-unburned areas with minimal ground flora diversity, the seedbank often evidences relict woodland conditions through its diversity and the site requirements of seedbank species (Hutchinson *et al*. 2005, Waldrop *et al*. 2008, Kinkead *et al*. 2013).

For these reasons and others, fire is increasingly considered in silvicultural systems and ecological restoration (Albrecht and McCarthy 2006, Dey and Schweitzer 2014, Kabrick *et al*. 2014). Benefits of fire treatments and woodland conditions are diverse and arguably critical to sustaining the oak ecosystem, including enhancing oak regeneration (Arthur *et al*. 2012, Brose *et al*. 2013); increasing understory plant species cover and richness (Hutchinson *et al*. 2005, Ratajczak *et al*. 2012, McCord *et al*. 2014); and improving diversity of native insects (Wood *et al*. 2011), birds (Reidy *et al*. 2014), and mammals (McShea *et al*. 2007, Starbuck *et al*. 2015). At larger scales, other benefits of woodlands may be realized, such as improved wildlife diversity through increasing early-successional habitat (Thompson and DeGraff 2001), decreased hazardous fuel loads, and increased climate change resilience (Brandt *et al*. 2014).

Incorporating fire science into management faces many challenges, particularly in the eastern US. Overall, fire's role in science, land management, and society is poorly understood and not well-founded (Pyne 2007). Compared to other natural sciences (e.g., forestry, wildlife, hydrology, botany, atmospheric science), fire research and professional scholarship has lagged behind and has not been of primary interest, despite being a linking theme. In Eastern hardwood forests, challenges and varying perspectives exist related to incorporating fire into forest management (Packard 1993, Matlack 2013, Stambaugh *et al*. 2015). A primary point of contention is that promoting fire use, particularly in hardwoods, can be perceived as inherently in conflict with other forest management objectives (i.e., fire prevention, wood fiber production, and human health promotion; Weldon 1996).

Historical fire regimes of eastern US oak woodlands vary at spatial scales from landscapes to regions (Guyette *et al*. 2003, 2006; Stambaugh *et al*. 2014*b*). Through time, historical fire intervals within Eastern oak woodlands can vary by an order of magnitude within the spatial extent of study sites (e.g., 1 km^2). When managing for woodland conditions with fire, it is not clear whether maintenance of woodland structures should focus on temporal or spatial variability in fire (or some combination). Understanding the historical distribution of woodlands, how fire regimes varied across landscapes, and how vegetation responded to fire regime departures would benefit understanding their successional pathways and designing management systems. Fire disturbance properties are often simplified by disregarding variability in metrics and how they change with scale (Falk *et al*. 2007). To characterize the temporal variability in fire regimes and to describe the spatial dependence of fire intervals, we analyzed eight multi-century fire scar records from two historically post oak (*Quercus stellata* Wangenh.)-dominated woodland landscapes. The objectives of this study were to: 1) reconstruct and contrast historical fire regime characteristics of sites within two different landscapes using fire scar analysis and, 2) quantify the effect of spatial scale of observation on fire frequency. With this information, we discuss the implications for historical data interpretation and oak woodland fire management. We expect that further understanding scaling theory of fire regimes will inform fire management decisions such as planning and employing burn treatments with characteristics (e.g., frequency, size, location, severity, patchiness) that historical fires once produced.

METHODS

Study Landscape and Site Descriptions

Study landscapes consisted of the Wichita Mountains Wildlife Refuge (WMWR) in the Cross Timbers region of southwest Oklahoma, USA, and Arnold Air Force Base (AAFB) in The Barrens region of south-central Tennessee, USA (Figure 1, Table 1). These landscapes are approximately 1150 km apart with contrasting physical, climatological, and biological properties (Figure 1). At each landscape, fire scar history data were collected from four sites across an approximately 100 km^2 area historically dominated by post oak woodlands. Data from the WMWR were collected from 2006 to 2011 and are reported in Stambaugh *et al*. (2009, 2014*a*), while data from AAFB were collected from 2004 to 2005 and are reported here.

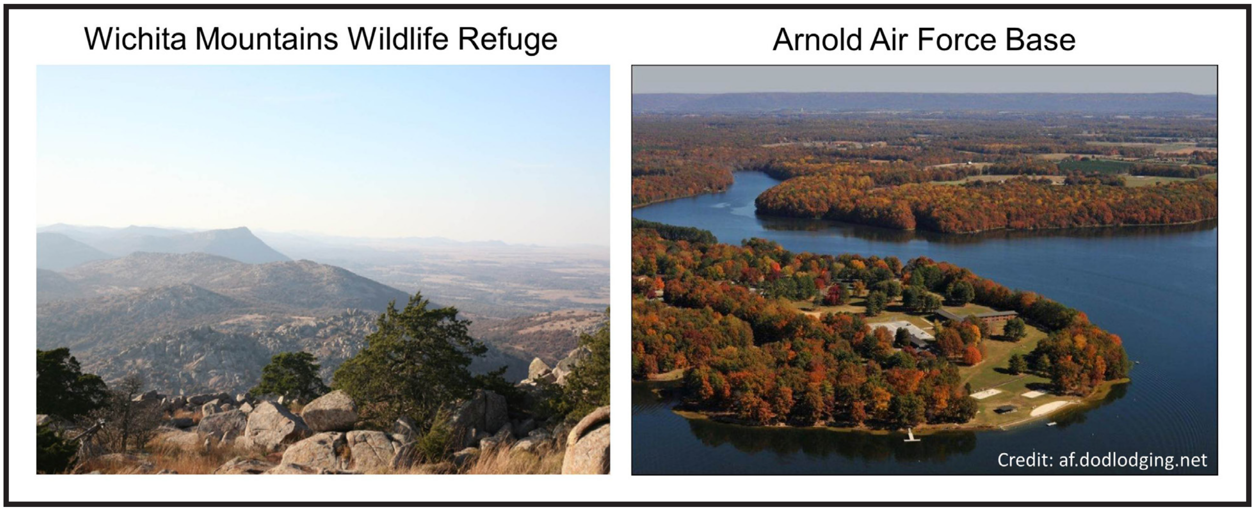


Figure 1. Study landscapes at the Wichita Mountains Wildlife Refuge, Oklahoma, USA, and Arnold Air Force Base, The Barrens, Tennessee, USA.

Table 1. Characteristics of the Wichita Mountains and The Barrens study landscapes.

	Wichita Mountains, Oklahoma	**The Barrens, Tennessee**
Ownership	US Fish and Wildlife Service	Arnold Air Force Base
Location	34° 45' 29" N, 98° 42' 21" W	35° 22' 16" N, 86° 5' 18" W
Terrain	mountainous (310 m elevation)	flat to rolling (43 m elevation)
Temperature min./max.	9.7 °C to 23.8 °C [a]	8.6 °C to 21.1 °C [b]
Annual precipitation	78 cm [a]	142 cm [b]
Land types	woodlands, grasslands, rock outcrops	forested uplands, wetlands
Substrate	rhyolite, cobbly	limestone
Climate	semi-arid and humid continental	humid continental
Surrounded by	Osage Plains	Nashville Basin and Highland Rim

[a] Annual mean from 1912 to 2012.
[b] Annual mean from 1893 to 2004.

Dendrochronology and Fire Scar History

At both landscapes, four study sites (0.3 km^2 to 1 km^2) were established following methods described in Stambaugh *et al.* (2014*a*). Within the boundary of AAFB, fire scar history sites were established at Huckleberry Ridge (HCK), Rowland Creek Headwaters (RCH), Saltwell Hollow (SLT), and Lemm Swamp (LEM) (Figure 2). Site data from WMWR are reported in Stambaugh *et al.* (2014*a*). Sites were selected non-randomly based on the availability of mature, fire-scarred post oaks and were spatially distributed to maximize distance between sites and incorporate variation in landscape characteristics. Trees at each site were evaluated for sampling adequacy based on bole soundness, evidence of basal wounding, external tree condition and architecture, and visual inspection of basal cross-sectional surfaces. Attempts were made to sample a range of tree sizes, ages, and growth rates throughout the full period (more than 250 years; Guyette and Stambaugh 2004). Cross sections (10 cm to 30 cm thick) were cut from the base of post oak trees

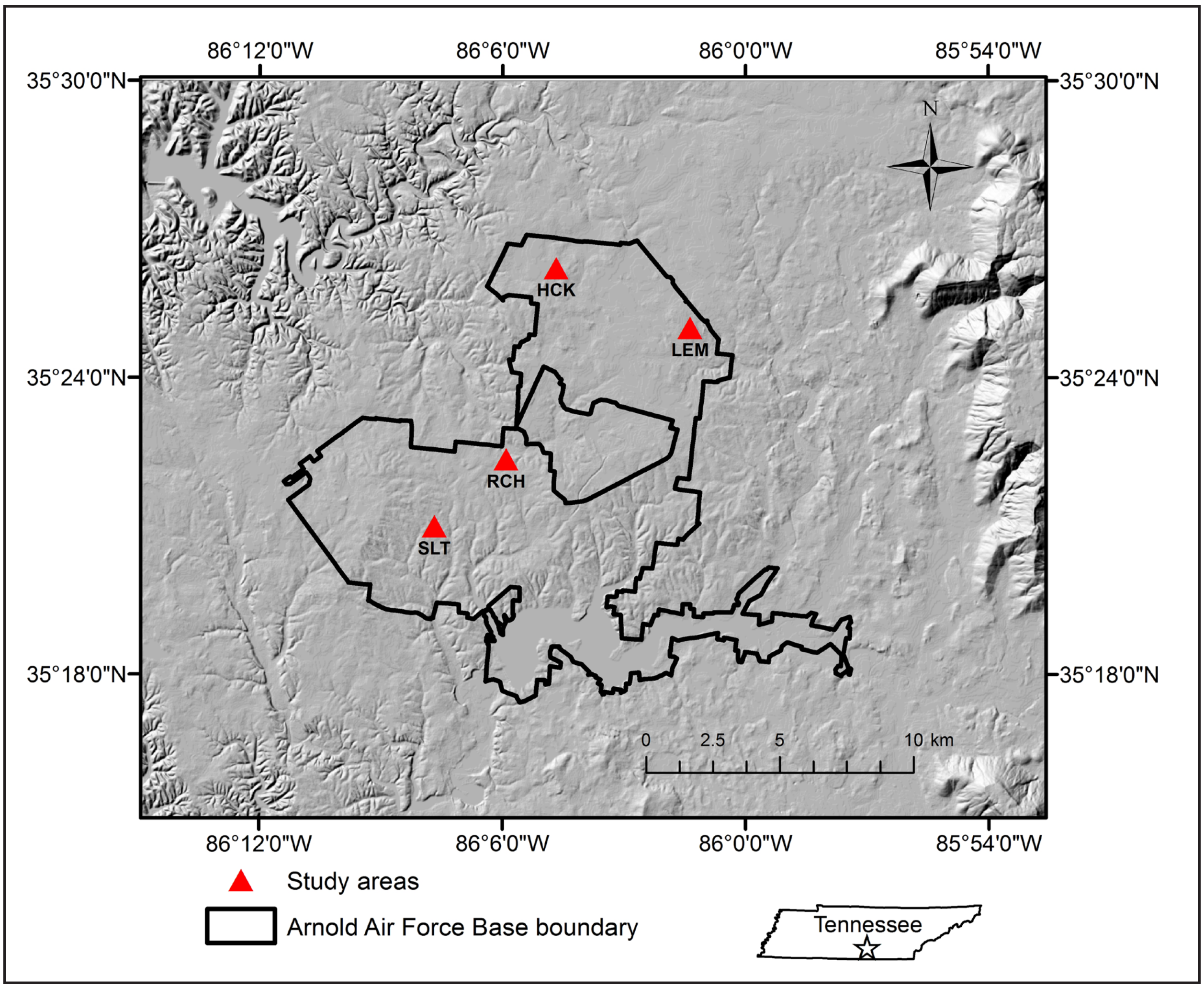


Figure 2. Hillshaded digital elevation model of landscape of Arnold Air Force Base (AAFB) and vicinity. Locations of study areas are represented by triangles with site codes (HCK = Huckleberry Ridge, RCH = Rowland Creek Headwaters, SLT = Saltwell Hollow, LEM = Lemm Swamp). Star symbol within inset map of Tennessee indicates the location of AAFB.

using a chainsaw. Cross sections were assigned a sample number, orientation, slope direction, and geographic location.

For each study site, fire scar history records consisted of 30 to 50 trees, >100 fire scars, and spanned 250 years or more. Fire scars on post oaks were dated using standard dendrochronological techniques (Stokes and Smiley 1968) utilizing master ring-width chronologies developed at the study areas (NOAA 2008; M. Stambaugh, University of Missouri, Columbia, Missouri, USA, unpublished data). Fire scars were dated to the year of cambial response to injury and, if during the growing season, to a within-ring location following methods described by Kaye and Swetnam (1999). Fire scars were identified by the presence of charcoal, callus tissue, and bark fissure scar patterns (Guyette and Stambaugh 2004). Composite fire scar chronologies were constructed by compiling fire scar data for individual study sites.

Data Analyses

Summary statistics for fire scars and intervals were calculated using FHAES and FHX software (Grissino-Mayer 2001). Fire intervals were defined as the number of years between two consecutive fire events. Mean fire intervals (MFIs) represented the average fire interval length in years. Median fire intervals (i.e., median intervals) were reported when the distribution of fire intervals fit the Weibull distribution. For AAFB, summary statistics were derived for four time periods associated with cultural changes: pre-EAS (pre-1834), Euro-American settlement (1834 to 1926), military ownership (post-1926), and the full period of record. The pre-EAS period at AAFB was defined as pre-1834 based on the timing of the Removal Act of 1830, when Native Americans were forced westward from the region (i.e., area containing study sites) with many groups ultimately residing in Oklahoma. Summary statistics of fire scar data at the WMWR are published in Stambaugh *et al*. (2014*a*) and reproduced here. At WMWR, time periods were defined as: pre-EAS (i.e., pre-Fort Sill, 1850), conflict (with Native Americans) and Euro-American settlement (1850 to 1901), public ownership (post-1901), and the full period of record (Stambaugh *et al*. 2014*a*).

For individual study sites (n = 8), fire intervals were derived from the composite fire scar chronologies (i.e., record of fires at the site based on all scars on all trees) and represented the occurrence of fire somewhere in the study site. We calculated summary statistics for fire intervals, percentages of trees scarred, and fire scar seasonality. Percentages of trees scarred were calculated by year then averaged across all years to generate a mean per site. Statistics were calculated separately for the different time periods of interest. For cases in which fire intervals spanned more than one period, intervals were assigned to the period with the majority of the interval years. Percentages of trees scarred were calculated for years in which at least four trees were represented in the record.

To describe the relationship between spatial scale of observation and MFIs, we compiled pre-EAS fire intervals at three spatial scales: individual trees (~1 m^2, n = 194 fire intervals), study sites (~1 km^2, n = 152 fire intervals), and landscapes (~100 km^2, n = 93 fire intervals). We calculated MFIs at the tree, site, and landscape scale for data from AAFB and WMWR separately. In addition, we calculated MFIs across these scales for all data compiled across both oak woodland study regions. Ranges and frequency distributions were plotted at each of these scales. Based on the work of Falk *et al*. (2007) that demonstrated fire frequency followed power-law behavior over space, we chose to represent the relationship between MFI and spatial scale with a negative-exponential model fit using SigmaPlot v12.3 software (SYSTAT Software, San Jose, California, USA). The presentation of the model is simply to demonstrate the relationship between MFI and spatial scale, not to provide prediction, since only three spatial scales were considered.

RESULTS

Fire History at AAFB, The Barrens, Tennessee

A total of 143 trees were sampled across the four fire history sites at AAFB (Table 2, Figure 3). The maximum and minimum time period spanned by sites was 1631 to 2004 (374 yr) and 1727 to 2004 (278 yr), respectively. A total of 423 fire scars and 205 fire intervals were identified from the four study sites (Table 2). When site data were pooled (i.e., landscape scale), 138 fire intervals were identified. All sites spanned a common period of 1727 to 2003. When sites were considered separately, composite fire intervals ranged from 1 yr to 35 yr, but when considering the entire landscape, composite fire intervals ranged from 1 yr to 26 yr. For the full period of record for each site, MFIs ranged from 2.9 yr to 6.5 yr. At decadal scales, sites shared some similar patterns in fire frequency through time including increased fire events in the few decades prior to 1800, decreased fire from about 1830 to 1850, and decreased fire in the latter half of the twentieth century (Figure 3). The MFIs among sites ranged from 3.3 yr to 5.2 yr pre-1834, to 2.5 yr to 10.3 yr from 1824 to 1926, to 5.7 yr to 10.3 yr post-1926. The trend of longer site MFIs during the pre-EAS period, to shortened MFIs following EAS, to longer MFIs in the latter twentieth century was shared by sites at both AAFB and WMWR (Tables 1 and 2). Annual burning (i.e., two fire years in sequence) occurred at all sites; however, at Lemm Swamp, this only occurred once while all other sites had at minimum 10 cases. The longest fire-free period occurred at HCK site from 1936 to 2003, a 67 yr period (Table 2, Figure 3).

Low severity fires (defined as ≤10% trees scarred in a fire event) were the most common across all sites. Overall, percentages of trees scarred at sites ranged from 2% to 60%, the same range as at WMWR (Table 3). Also similar between the landscapes, the percentages of trees scarred at each site trended downward between pre-EAS and settlement periods, but generally trended upward from settlement to current day (Tables 1 and 2, Figure 3). Based on tree ages, no evidence of complete stand-replacing fires occurred at any sites within AAFB or the WMWR during the period of record. Fire seasonality was dominated by dormant season fires. Both HCK and RCH sites had exclusively dormant season fires. Growing season scars constituted 3% at both the SLT and LEM sites.

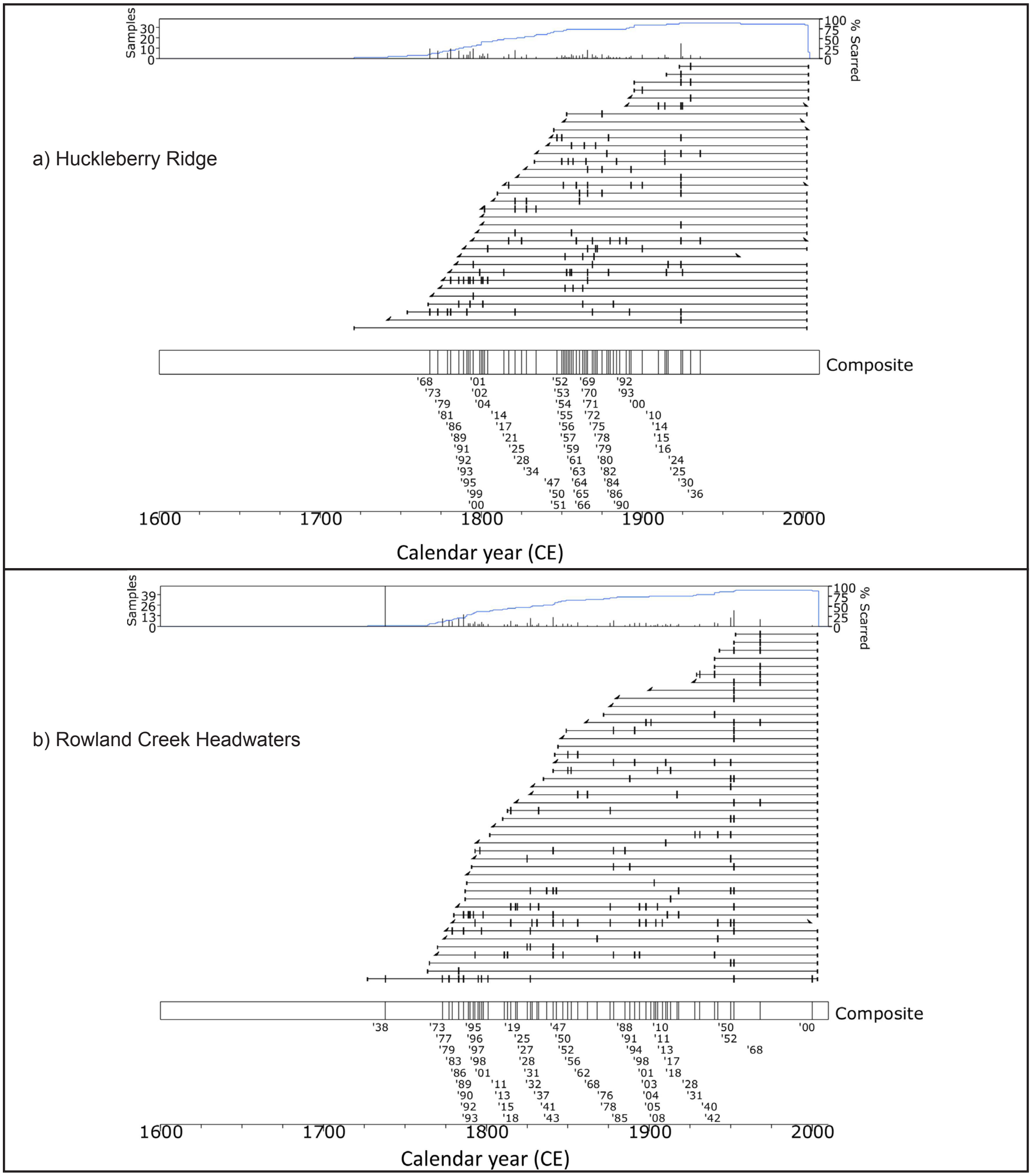
Contrasting Fire Regimes between Tennessee and Oklahoma

Many similarities existed between the historical fire regimes in Tennessee and Oklahoma (Tables 1 and 2, Figure 4). Sites spanned similar time periods, likely due to presence of post oak reaching maximum longevity. At sites in both landscapes, fire events during the pre-EAS period were generally less frequent, with slightly higher average percentages of trees scarred compared to the following Euro-American settlement period. For the full period of record, fires were more frequent at sites (1 km^2) in Tennessee than in Oklahoma, but at the landscape scale (100 km^2), they were similar (MFI = 2.2 years at AAFB versus 2.6 years at WMWR). Both landscapes had primarily dormant season fires with slightly greater numbers of growing season fires in Oklahoma (although seasonality was undeterminable for many scars). Ranges of percentages of trees scarred were widest in the pre-EAS period for both landscapes (Tables 1 and 2). Similarly, mean percentages of trees scarred decreased in the settlement era when overall burning frequency increased among sites.

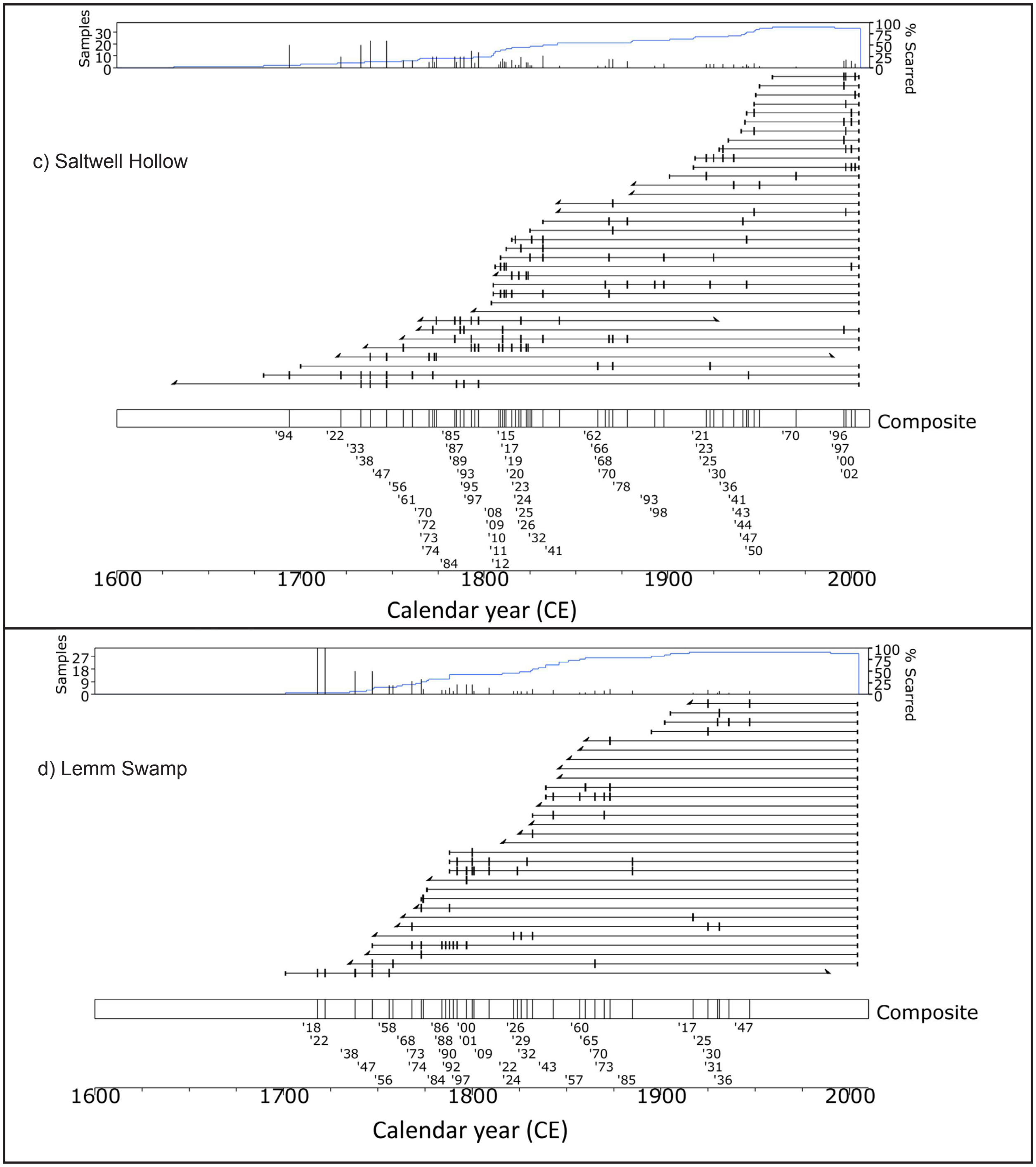
Table 2. Fire scar history data at the site and landscape scale for Arnold Air Force Base. Data are stratified by time periods associated with cultural changes. Data for fire intervals on individual trees are not shown in this table but can be viewed in Figures 3 and 5.

	Huckleberry Ridge	Rowland Creek Headwaters	Saltwell Hollow	Lemm Swamp	All sites
Spatial extent (km^2)	~1	~1	~1	~1	~100
All years					
Time period	1721 to 2003	1727 to 2003	1631 to 2004	1701 to 2004	1631 to 2004
Trees (*n*)	34	44	35	30	143
Fire intervals (*n*)	58	58	54	35	138
Mean fire interval (yr)	2.9	4.52	5.7	6.5	2.23
Fire interval range (yr)	1 to 13	1 to 35	1 to 28	1 to 32	1 to 26
Median interval (yr)	2.4	3.2	3.9	5.2	na
Mean trees scarred (%)	9.4	8.9	16.1	11.6	38.4[a]
Range trees scarred (%)	3 to 39	2 to 40	3 to 60	3 to 38	25 to 100[a]
Fire scars (*n*)	112	135	117	59	423
Dormant season fires (%)	100	100	96	98	98
Growing season fires (%)	0	0	4	2	2
Undetermined (%)	0	0	0	0	0
Prior to Euro-American settlement period (before 1834)					
Time period	1721 to 1834	1727 to 1834	1631 to 1834	1701 to 1834	1631 to 1834
Trees (*n*)	22	25	18	17	82
Fire intervals (*n*)	20	24	31	22	60
Mean fire interval (yr)	3.3	3.92	4.45	5.18	2.33
Fire interval range (yr)	1 to 10	1 to 35	1 to 28	1 to 16	1 to 24
Median interval (yr)	2.93	2.48	3.1	4.29	1.64
Mean trees scarred (%)	13.6	10.3	21.3	14.9	43.3[a]
Range trees scarred (%)	5 to 29	4 to 30	6 to 60	6 to 38	25 to 100[a]
Fire scars (*n*)	33	38	62	36	169
Dormant season fires (%)	100	100	97	97	97
Growing season fires (%)	0	0	3	3	3
Undetermined (%)	0	0	0	0	0
Euro-American settlement period (1834 to 1926)					
Time period	1834 to 1926	1834 to 1926	1834 to 1926	1834 to 1926	1834 to 1926
Trees (*n*)	33	36	26	30	125
Fire intervals (*n*)	36	25	10	8	60
Mean fire interval (yr)	2.53	3.24	8.4	10.25	1.52
Fire interval range (yr)	1 to 13	1 to 8	2 to 23	3 to 32	1 to 4
Median interval (yr)	1.95	na	na	na	1.43
Mean trees scarred (%)	7.28	6.07	9.45	7.44	34.17[a]
Range trees scarred (%)	3 to 39	3 to 23	4 to 19	3 to 12	25 to 75[a]
Fire scars (*n*)	74	53	23	17	167
Dormant season fires (%)	99	100	100	100	100
Growing season fires (%)	1	0	0	0	0
Undetermined (%)	0	0	0	0	0
Military use (1926 to 2004)					
Time period	1926 to 2003	1926 to 2003	1926 to 2004	1926 to 2004	1926 to 2004
Trees (*n*)	34	44	34	30	142
Fire intervals (*n*)	1	7	11	3	17
Mean fire interval (yr)	na	10.29	6.55	5.67	4.35
Fire interval range (yr)	na	2 to 32	1 to 26	1 to 11	1 to 26
Median interval (yr)	na	na	4.25	na	2.7
Mean trees scarred (%)	7.5	14.71	8.5	5	36.11[a]
Range trees scarred (%)	6 to 9	2 to 40	3 to 18	3 to 7	25 to 75[a]
Fire scars (*n*)	5	44	32	6	87
Dormant season fires (%)	100	100	91	100	92
Growing season fires (%)	0	0	9	0	8
Undetermined (%)	0	0	0	0	0

[a] based on percentages of sites scarred.



Figures 3a and 3b. Post oak fire scar history charts of two of the four individual study sites at Arnold Air Force Base in The Barrens region of Tennessee, USA. On study site charts, top boxes indicate numbers of trees recording (blue line) and percentages of trees scarred (vertical bars) through time. Below, horizontal lines represent the periods of tree-ring record for individual trees. Bold vertical ticks on horizontal lines indicate fire scar years. On the left ends of lines, vertical ends indicate pith years while diagonal ends indicate inner ring year (rings missing to center). On the right ends of lines, vertical ends indicate bark years while diagonal ends indicate outer ring years (rings missing to bark). A composite of all fire years at the site is given at the bottom of charts.



Figures 3c and 3d. Post oak fire scar history charts of two of the four individual study sites at Arnold Air Force Base in The Barrens region of Tennessee, USA. On study site charts, top boxes indicate numbers of trees recording (blue line) and percentages of trees scarred (vertical bars) through time. Below, horizontal lines represent the periods of tree-ring record for individual trees. Bold vertical ticks on horizontal lines indicate fire scar years. On the left ends of lines, vertical ends indicate pith years while diagonal ends indicate inner ring year (rings missing to center). On the right ends of lines, vertical ends indicate bark years while diagonal ends indicate outer ring years (rings missing to bark). A composite of all fire years at the site is given at the bottom of charts.

Table 3. Fire scar history data at the site and landscape scale for the Wichita Mountains. Data are stratified by time periods associated with cultural changes. Data for fire intervals on individual trees are not shown in this table, but can be viewed in Figure 5 or Stambaugh *et al.* 2014*a*.

	Hollis Canyon	French Lake	Rain Gauge Flat	Cache Creek	All sites
Spatial extent (km^2)	~1	~1	~1	~1	~100
All years					
Time period	1720 to 2010	1712 to 2005	1746 to 2009	1637 to 2010	1637 to 2010
Trees (*n*)	46	54	46	43	189
Fire intervals (*n*)	34	59	34	34	112
Mean fire interval (yr)	7.94	4.73	7.09	7.82	2.63
Fire interval range (yr)	1 to 27	1 to 19	1 to 26	1 to 66	1 to 12
Median interval (yr)	6.14	3.77	5.53	4.49	na
Mean trees scarred (%)	10.31	5.88	11.77	9.22	37.22 [a]
Range trees scarred (%)	2 to 29	2 to 36	2 to 60	3 to 50	25 to 100 [a]
Fire scars (*n*)	105	122	102	91	420
Dormant season fires (%)	88	78	80	97	86
Growing season fires (%)	0	2	6	2	3
Undetermined (%)	12	20	14	1	12
Prior to Euro-American settlement period (before 1850)					
Time period	1727 to 1850	1712 to 1850	1746 to 1850	1637 to 1850	1637 to 1850
Trees (*n*)	31	38	33	31	133
Fire intervals (*n*)	12	20	13	11	42
Mean fire interval (yr)	8.83	6.25	6.46	12.27	3.21
Fire interval range (yr)	2 to 25	1 to 19	1 to 17	3 to 53	1 to 10
Median interval (yr)	6.7	5.53	5.42	9.45	2.87
Mean trees scarred (%)	11.7	9.2	19.64	12.56	36.43 [a]
Range trees scarred (%)	3 to 29	3 to 36	3 to 60	3 to 33	25 to 100 [a]
Fire scars (*n*)	24	49	53	29	155
Dormant season fires (%)	92	69	81	100	86
Growing season fires (%)	0	2	0	0	1
Undetermined (%)	8	29	19	0	14
Conflict and settlement period (1850 to 1901)					
Time period	1850 to 1901	1850 to 1901	1850 to 1901	1850 to 1901	1850 to 1901
Trees (*n*)	46	53	34	36	169
Fire intervals (*n*)	11	19	13	18	38
Mean fire interval (yr)	3.55	2.42	3.23	2.72	1.29
Fire interval range (yr)	1 to 8	1 to 7	1 to 8	1 to 7	1 to 3
Median interval (yr)	3.35	na	2.99	2.42	na
Mean trees scarred (%)	8.58	4.65	5.23	7.26	41.67 [a]
Range trees scarred (%)	3 to 19	2 to 10	3 to 12	3 to 32	25 to 100 [a]
Fire scars (*n*)	33	38	26	45	142
Dormant season fires (%)	85	84	77	93	85
Growing season fires (%)	0	3	15	4	6
Undetermined (%)	15	13	8	2	10
Public ownership (1901 to 2010)					
Time period	1901 to 2010	1901 to 2005	1901 to 2009	1901 to 2010	1901 to 2010
Trees (*n*)	46	54	46	43	189
Fire intervals (*n*)	9	18	6	4	31
Mean fire interval (yr)	10.67	5.22	16.67	19.25	3.42
Fire interval range (yr)	1 to 27	1 to 19	7 to 26	2 to 66	1 to 12
Median interval (yr)	8.85	4.04	16.33	8.70	2.89
Mean trees scarred (%)	11	3.68	9	10.4	32.28 [a]
Range trees scarred (%)	2 to 11	2 to 10	2 to 23	3 to 17	25 to 75 [a]
Fire scars (*n*)	52	35	23	20	130
Dormant season fires (%)	88	83	83	95	87
Growing season fires (%)	0	3	9	5	4
Undetermined (%)	12	14	9	0	9

[a] based on percentages of sites scarred.

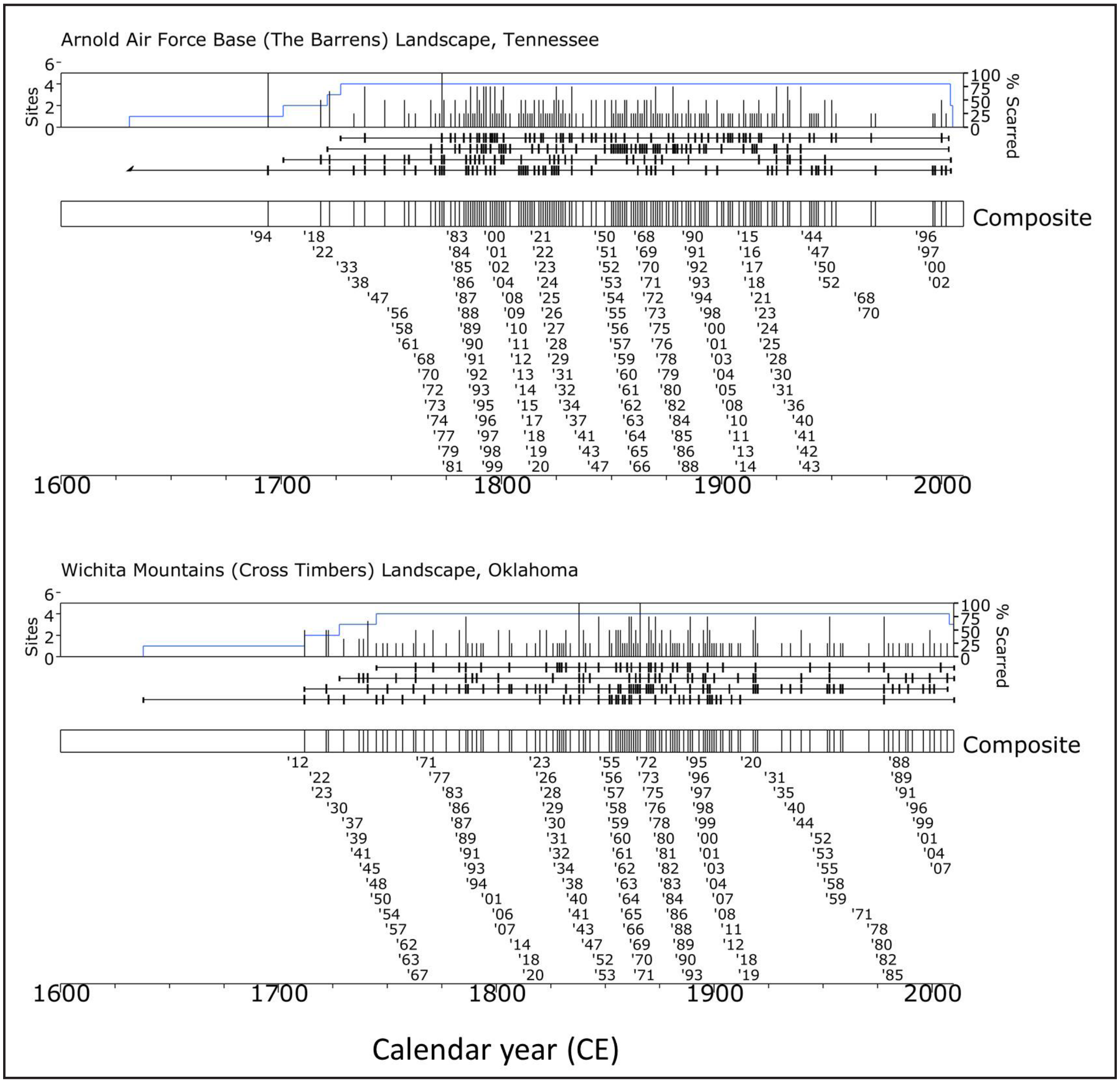


Figure 4. Fire scar history diagrams for Arnold Air Force Base and Wichita Mountains post oak woodland landscapes (areas of approximately 100 km^2). Top boxes indicate number of sites recording (blue line) and percentages of sites scarred (vertical bars) through time. Below, horizontal lines represent the periods of record of each site (i.e., each horizontal line represents all trees combined from sites shown in Figure 3). Fire scar dates at the bottom of this chart represent the occurrence of fire events within the landscape extent (~100 km^2).

Spatial Scale Dependence of Pre-EAS MFIs

Pre-EAS fire intervals decreased from the spatial extent of individual trees (1 m^2), to sites (1 km^2), to landscapes (100 km^2) (Figure 5). Fire intervals on individual trees ranged from 1 yr to 38 yr at AAFB, and 1 yr to 90 yr at WMWR. Mean fire intervals on individual trees were 8.7 yr at AAFB and 19.8 yr at WMWR. At the site scale, fire intervals ranged from 1 yr to 35 yr (mean = 4.3) at AAFB, and 1 yr to 53 yr (mean = 8.0) at WMWR. At the landscape scale, fire intervals ranged from 1 yr to 24 yr (mean = 2.3) at

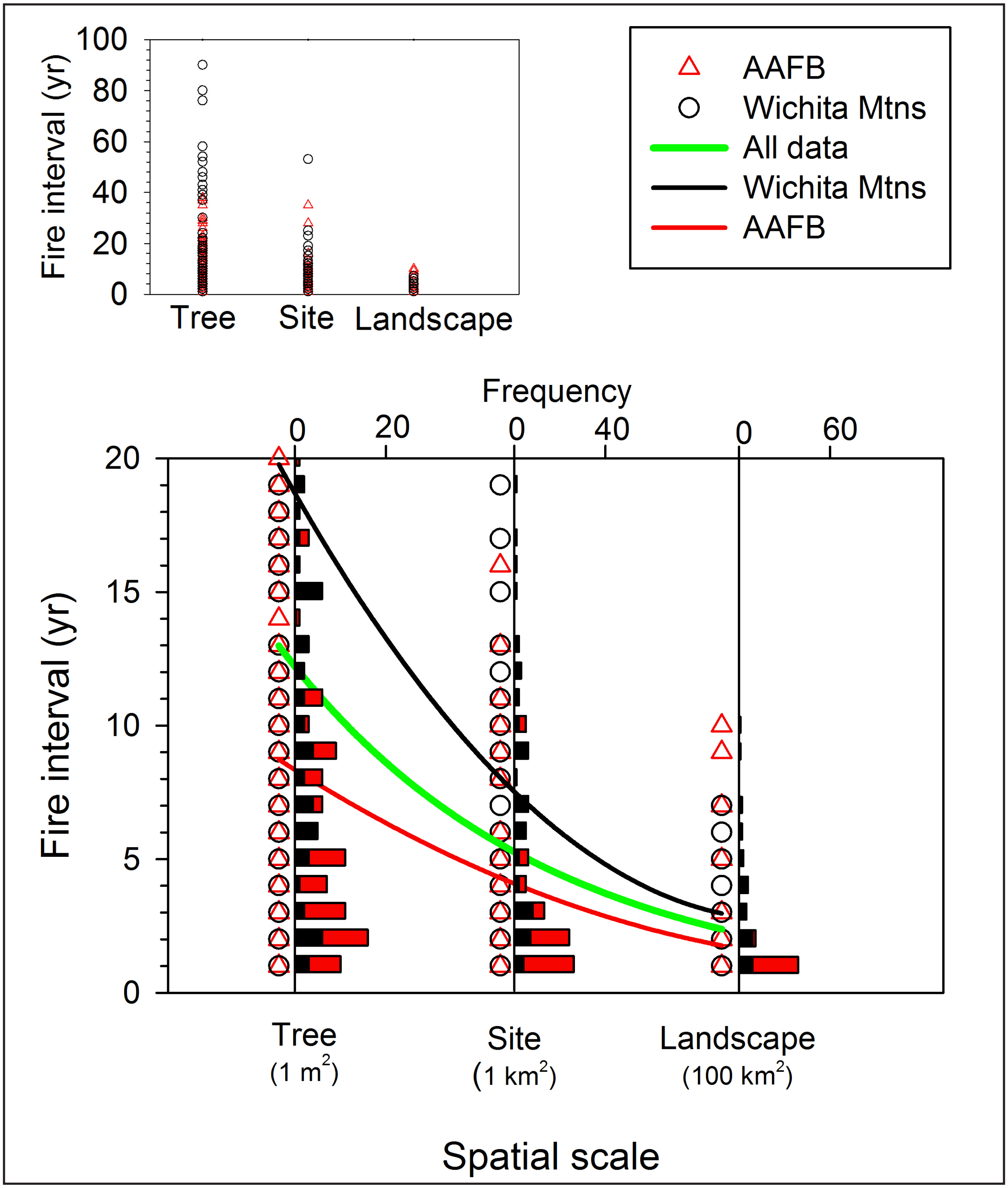


Figure 5. Pre-EAS period fire intervals at the scales of individual tree, site, and landscape. Fire intervals are separated by site indicated by triangle and circle symbols (see graph at top left for full range of observed intervals). Horizontal bars represent the frequency of observations for each interval. Curves depict the negative exponential relationship between mean fire interval (MFI) and scale. The MFIs at each spatial scale were fit with a negative exponential curve. Separate curve fits are shown for data from all oak woodland sites and the two study landscapes separately.

AAFB, and 1 yr to 10 yr (mean = 3.2) at WMWR. The negative exponential equation relating pre-EAS period mean fire interval to spatial extent was given as:

$$MFI = 12.96 \times e^{(-0.82 \times area)}, \qquad (1)$$

where MFI = mean fire interval at the respective spatial extent, area is in km^2 (Figure 5).

DISCUSSION

Fire scars on trees are spatially explicit data, which can be an advantage over other historical sources such as documentary records. For example, personal observations like Swallow's (1859) commonly cited description of annually occurring fires in Missouri oak woodlands rarely include a spatial reference. Based on our results, annually occurring fires were limited (maximum of 10 times over a three-century period at the study site extent) and would not be the MFI of post oak woodlands, unless considering landscape fire occurrence rates for areas >3 km^2 (based on Equation 1 and on fire data from four sites per landscape). Other evidence, such as experimental burn studies, also suggests that long-term frequent (<2 yr) to annual burning is too frequent to sustain tree recruitment in oak forest communities (Peterson and Reich 2001, Knapp *et al*. 2015). One explanation for how fires could have been reported to have historically burned annually while tree recruitment was sustained might be due to only portions of a given landscape burning in a single year when fire occurrence was reported.

Disturbances such as fire vary by spatial and temporal scales due to differences in influences of drivers and controls (Turner 1987). Understanding signatures in spatial and temporal dependence reveals clues to the type and relative importance of environmental controls. In the US, networks of historical fire scar data have shown how fire regime drivers and controls vary from tree to subcontinental scales, including their relevance to vegetation change, human populations and cultures, and climate conditions (Guyette *et al*. 2002, 2006; Taylor and Skinner 2003; Falk *et al*. 2011). In general, we found fire to be more frequent in Tennessee than in Oklahoma, particularly pre-EAS. This result is somewhat surprising considering that Tennessee sites are generally wetter, more humid, and not in a significantly more lightning-ignition prone region. Frequent fire regimes, particularly with the aforementioned conditions, are commonly attributed to anthropogenic influence (Guyette *et al*. 2002). McClain *et al*. (2010) found more frequent fires during a pre-EAS period in a post oak woodland in Illinois, USA (MFI = 1.97 yr from 1776 to 1850), while Guyette *et al*. (2003) found less frequent fires in a southern Indiana, USA, woodland (MFI = 23 yr from 1620 to 1820). Other studies exist from post oak woodlands in Oklahoma and Texas, USA, and these report pre-EAS MFIs between 3.3 yr to 6.7 yr (Clark *et al*. 2007, DeSantis *et al*. 2010, Allen and Palmer 2011, Stambaugh *et al*. 2011)—values that fall within the range of data presented here. All of the post oak fire data mentioned above were derived from sites within the western and north-central portion of the range of post oak and, therefore, may not characterize conditions farther east and south with wetter and warmer climates, varied vegetation and fuels, and differing fire regime characteristics (i.e., fire seasonality, ignition sources).

Scale dependence of historical fire regimes could influence fire management planning, the interpretation of natural and documentary archival data, and models that simulate landscape fire disturbance (e.g., LANDIS; Wang *et al.* 2014). In this study, fire scar data were used to explore the scale dependence of fire intervals from tree to landscape scales. Results describing how fire intervals vary by extent are among the first reported in the eastern US; additional studies are needed to test these findings. Fire scar wounding measurements paired with fire behavior and burn area information would likely improve relationships and interpretation at each extent. One expected bias of our fire scar data is that the frequency of fire recorded at the individual tree scale was probably lower than actually occurred due the fact that individual trees may not record all fire events. In this case, the characterization of mean fire interval at the individual tree extent could be more frequent than our model (Equation 1) would suggest. Additional biases may affect our results, such as our inability to randomly select study site locations within landscapes.

Relevance to Oak Woodland Ecology and Management

Fire history data provide perspective, and possibly a basis, for oak forest community management in the eastern US. The value of fire history data is not only that they inform management, but also that they further understanding of scale effects, landscape fire heterogeneity, and long-term vegetation dynamics of active fire regimes. These data can span more than 300 years and identify processes that vary on time scales much longer than professionals' careers or experiments. This is particularly relevant to open oak canopy structures such as woodlands and savannas, within which fire disturbance may have been the most important factor responsible for their existence and conditions (Dey and Kabrick 2015), but for which little guidance exists within written documentation, living memory, or management experience.

For present day management of fire-dependent communities, it is important to remember that, historically, forest community structures and compositions encountered during EAS most likely did not previously undergo extensive cutting treatments, despite being the most common vegetation manipulation technique in restoration projects today. Further, historical fire conditions (i.e., severity, extent) were not bound by modern-day societal and physical barriers (e.g., safety, emissions, roads, changing land uses), likely allowing for a greater potential for more extensive, longer duration, and higher severity fires to occur historically. Generally, in Eastern hardwood forests, the effects of cutting vegetation are not a surrogate for fire, particularly in regard to the ground-belowground impacts and thermal selection for smaller-sized, thin bark vegetation following low severity fires (Waldrop *et al*. 2008). Indeed, cutting treatments may be a necessary activity in woodland and savanna restoration to achieve the desired structure of trees due to the limited ability of low intensity fires to reduce the density of larger diameter trees (e.g., trees >10 cm dbh), almost regardless of species (Arthur *et al*. 2015). Bark thickness on larger diameter trees can be sufficient to protect the cambium from fire-girdling during low intensity fires even for what are considered fire-sensitive species (Hutchinson *et al*. 2005). Mechanical thinning of the overstory, in conjunction with prescribed burning, is commonly combined in initial restoration efforts until desired structure is achieved that can then be more easily maintained by a regime of prescribed burning (e.g., Hutchinson *et al.* 2005, Waldrop *et al*. 2008, Kinkead *et al*. 2013).

It is important to consider the spatial and temporal variation in historical fire regimes and how those resulted in the mosaic of prairie, savanna, woodland, and forest as fire interacted with topography and other site factors that influenced ignition potential and fire behavior. Heterogeneity in fire coverage and effects probably affected historical woodland conditions (i.e., presence or absence, tree density, and species). Prescribed fire to restore woodlands is commonly applied to hundreds to thousands of hectares at a time. Our results suggest that, within the extent of a landscape, great variability exists in fire frequency. Recognition and quantification of these disturbance properties could aid in understanding the ecology and management of fire-dependent natural communities. Within safety, social acceptance, and human resource limitations, fire treatments (e.g., ignitions, behavior) that are allowed to be influenced by environmental constraints (e.g., seasonality, terrain influences), promote mosaics of natural communities and fulfillment of the range of natural variation in composition and structure within a community type.

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