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Temporal and spatial patterns in fire occurrence during the establishment of mixed-oak forests in eastern North America

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Abstract

Question: What was the role of fire during the establishment of the current overstory (ca. 1870-1940) in mixed-oak forests of eastern North America?

Location: Nine sites representing a 240-km latitudinal gradient on the Allegheny and Cumberland Plateaus of eastern North America.

Methods: Basal cross-sections were collected from 225 trees. Samples were surfaced, and fire scars were dated. Fire history diagrams were constructed and fire return intervals were calculated for each site. Geographic patterns of fire occurrence, and fire-climate relationships were assessed.

Results: Fire was a frequent and widespread occurrence during the formation of mixed-oak forests, which initiated after large-scale land clearing in the region ca. 1870. Fire return ranged from 1.7 to 11.1 years during a period of frequent burning from 1875 to 1936. Fires were widespread during this period, sometimes occurring across the study region in the same year. Fires occurred in a variety of climate conditions, including both drought and non-drought years. Fires were rare from 1936 to the present.

Conclusions: A variety of fire regime characteristics were discerned. First, a period of frequent fire lasted approximately 60 years during the establishment of the current oak overstory. Second, fire occurred during a variety of climate conditions, including wet climates and extreme drought. Finally, there was within-site temporal variability in fire occurrence. These reference conditions could be mimicked in ongoing oak restoration activities, improving the likelihood of restoration success.

Keywords: Deciduous forest; Dendroecology; Disturbance; Fire scar; Oak; *Quercus alba*; Tree ring.

Nomenclature: Gleason & Cronquist (1991).

Introduction

Fire is an important disturbance process in many forest ecosystems of North America (Pyne 1982; Christensen 1993). Fires affect forests by decreasing tree density, reducing fuel loads and altering nutrient dynamics (Moore et al. 1999; Wan et al. 2001; Tramell et al. 2004; Albrecht & McCarthy 2006). Some North American ecosystems have been affected by periodic fire for at least the last several millennia (Pyne 1982; Delcourt et al. 1998) and fire has been linked to the regeneration and recruitment of some forest species (Shumway et al. 2001; Brown & Wu 2005). Since ca. 1930, fire has been excluded from most forests in eastern North America, often leading to significant alterations in their structure and function (Oberle 1969; Dodge 1972). In order to restore historical ecosystem characteristics, a program of prescribed fire has been implemented in a variety of ecosystems (Anderson et al. 1983; Moore et al. 1999; Hutchinson et al. 2005).

Mixed-oak forests of eastern North America are undergoing a successional dynamic that has been linked to an absence of fire in their recent history. These forests are characterized by an overstory dominated by oaks (*Quercus* spp.) and sub-canopy strata clearly dominated by maples (*Acer* spp.; Lorimer 1984; McCarthy et al. 1987; Goebel & Hix 1996; Arthur et al. 1999). The paucity of oak in regeneration layers of these forests has been linked to an absence of fire in the recent past (Crow 1988; Abrams 1992), and a successional dynamic toward increased maple importance is ongoing (McEwan & Muller 2006). To impede succession from oak to maple, prescribed fire has been applied in oak forests, but the success of these fire restoration efforts has been limited (Albrecht & McCarthy 2006; Blankenship & Arthur 2006).

The use of prescribed fire in modern landscapes is often guided by an understanding of fire as a historical disturbance process (Moore et al. 1999; Swetnam et al. 1999; Egan & Howell 2001). Many researchers have relied on dendrochronological analysis of fire-scarred tree samples as a resource for documenting historical fire regimes (Veblen & Kitzberger 2002; Fulé et al. 2003; Guyette & Spetich 2003). Extensive fire histories have been developed for conifer forests of western North America (Grissino-Mayer & Swetnam 2000; Brown 2006; Van Horne & Fulé 2006) and in oak forests of the Ozark Mountain Region (Cutter & Guyette 1994; Guyette & Spetich 2003; Soucy et al. 2005); fire history in other oak forests is less well understood (but see: Shumway et al. 2001; McCarthy et al. 2001; Schuler & McClain 2003).

We conducted a tree-ring analysis of fire history in mixed-oak forests of eastern North America. The principal objective of this work was to identify key features of the fire regime that existed during the establishment (ca. 1870-1940) of the current overstory in oak dominated communities. We also addressed the following two questions:

Question 1: Was historical fire occurrence related to climate conditions? In many conifer forests, fire occurrence has been clearly linked with drought which preconditioned fuels to ignite and augmented fire spread (Grissino-Mayer et al. 2004; Brown 2006). The relationship between drought and fire occurrence is less well understood in oak forests of eastern North America.

Question 2: Did fire occur across broad areas of the landscape during the same year in these oak communities? Unlike some ecosystems of western North America, eastern oak forests are divided into relatively small parcels that are often bounded by features that would serve as a fire break (e.g. cleared land, waterways). This landscape structure would limit fire spread and make broad-ranging fires from a single ignition source highly unlikely.

Methods

Study area

Study sites were located on the Allegheny Plateau of southeastern Ohio and the Cumberland Plateau of eastern Kentucky (Fig. 1). The topography of the study region is characterized by steep terrain with narrow ridges and shallow valleys (Braun 1950; Sutherland & Hutchinson 2003). Regional climate is humid and continental with no distinct dry season. Mean annual temperature and precipitation are ca. 11 °C and 1020 mm, respectively (Sutherland & Hutchinson 2003).

The study area is within the Mesophytic Forest Region (MFR) described by Braun (1950) and Dyer (2006). The forests of this region are characterized by contrasting community types that occur over topographic gradients (Muller 1982; Braun 1950). Upper slopes, and mid-slopes on south-facing aspects, are sites of oak dominance in modern stands (McEwan & Muller 2006), and at least some of these sites have exhibited oak dominance throughout the recent past. For instance, according to Joseph Gibbon, who traveled in southeastern Ohio (ca. 1804) prior to widespread Euro-American settlement, the landscape was 'well timbered' chiefly of 'white and black oaks, red, Spanish, and chestnut oak' (Walker 1983). This commentary is supported by settlement era witness-tree data from southeastern Ohio where *Quercus alba* was vastly more important than other species (Dyer 2001; Hutchinson et al. 2003). Currently these oak communities typically exhibit an overstory where the dominant species *Q. alba, Q. prinus* and *Q. velutina* are intermingled with hickories (e.g. *Carya ovata, C. tomentosa*) and a mix of other species (Braun 1950). In contrast to the overstory, maples (*Acer rubrum* and *A. saccharum*) typically have vastly greater densities than oaks in sub-canopy strata (McCarthy et al. 1987; McEwan et al. 2005). Other important species in the forest understory include *Cornus florida*, *Sassafras albidum* and *Oxydendrum arboreum* (Braun 1950).

Forests of the study region have experienced a myriad of disturbances. Native Americans influenced these forests through burning, species transplantation and land clearance (Williams 1989; Denevan 1992; Whitney 1994). The incursion of Euro-Americans into the region ca. 1780 resulted in a series of large-scale disturbances. Forests were cleared for agricultural plots,

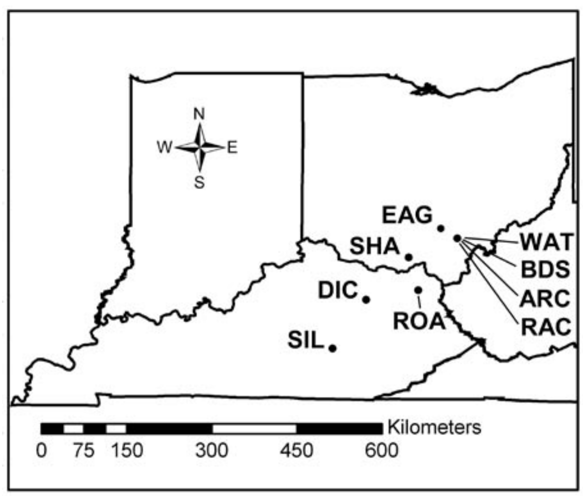

Fig. 1. Study site locations across southeastern Ohio and eastern Kentucky, USA. Site names are represented by three letter codes. Note that a group of four sites were too close together to create individual dots at this scale and are represented by a single dot with lines drawn to the codes. These sites were still separated, at a minimum, by 1 km distance divided into several watersheds.

for building materials, and to provide fuel for the iron industry (Stout 1933; Williams 1989; Hutchinson et al. 2003). The cumulative effect of these land-use activities was broad-scale deforestation of the region by the late 1800s (Whitney 1994). Beginning ca. 1900, a suite of cultural changes allowed for broad-scale forest re-growth (Williams 1989; Whitney 1994). Since ca. 1930 forests in the region have been influenced by a variety of factors including partial timber harvesting and the loss of species due to introduced pathogens (e.g. chestnut blight; McCormick & Platt 1980).

Site selection, sample collection and lab methods

Samples were collected from six sites in southeastern Ohio and three sites in eastern Kentucky (Table 1). These sites represented an approximately 240-km latitudinal gradient (Fig. 1). Sites were located on oak-dominated upper slopes and all but two were selected opportunistically based on the availability of stumps following timber harvesting. Sites of opportunistic sampling included EAG, BDS, RAC, and SHA in Ohio, and ROA, DIC, and SIL in Kentucky (Table 1, Fig. 1). Opportunistic sampling entailed site surveys to mark stumps containing historical wounding and a second trip during which stem cross-sections were collected. The sampling operation for two Ohio sites, WAT and ARC, included the felling of standing live stems followed by collection of stem cross-sections (McEwan et al. in press). Only those stems found by McEwan et al. (in press) to contain wounds were used in the present analysis. At each site, 20 to 40 samples were collected, and sampling areas were 10-40 ha. Sampling took place intermittently from July of 2002 to December of 2005.

Following collection, each sample was surfaced with a power planer and then sanded with a belt sander equipped with a series of increasingly fine grit belts. Fire history information was then collected from each sample following typical dendrochronology methods (Stokes and Smiley 1968). Graphical ('skeleton') plots that highlight years of abnormally low tree growth were constructed and then used to cross-date samples against a regional master chronology (Stokes & Smiley 1968). All wound events were dated and seasonality of wounding was noted. Finally, the diameter of the stem at the time of each wound was measured by summing two radii from the pith to the tree-ring in which the wounding occurred.

Table 1. Fire-history study sites in oak forests of southeastern Ohio and eastern Kentucky, USA. Sites are arranged from north to south.

Study site	Code	State	Location	Nr of samples
Eagle Mill	EAG	OH	39.34° N, 82.72° W	26
Watch Rock	WAT	OH	39.20° N, 82.38° W	33
Ball Diamond	BDS	OH	39.19° N, 82.41° W	22
Arch Rock	ARC	OH	39.19° N, 82.38° W	31
Raccoon Creek	RAC	OH	39.17° N, 82.39° W	25
Shawnee	SHA	OH	38.68° N, 83.21° W	20
Road Branch	ROA	KY	38.24° N, 83.38° W	20
Dickerson Hollow	DIC	KY	38.11° N, 83.59° W	20
Silver Creek	SIL	KY	37.54° N, 84.25° W	28

Analytical methods

Wound data were entered into the fire scar analysis software FHX2 (Grissino-Mayer 2001; Forest Research Tools Inc. 2006). All wound events were plotted and a composite chronology was developed for each site. The composite chronology consisted of (fire) years, during which scars were found on at least three trees within a given site (e.g. Brose & Waltrop 2006). Exceptions were made for years in which wounding occurred on two samples and the sample size was < 10 at that point in time. This requirement acts as a filter for wounds caused by non-fire sources, which can be morphologically identical to fire scars, but typically only affect one tree during any given year. Fire-wounding is a landscape phenomenon typically affecting many trees during any given year (McEwan et al. in press).

Summary statistics and fire return intervals were then calculated using FHX2 (Grissino-Mayer 2001). Basic fire return parameters, such as the mean and median interval between fires, were calculated for each site and averaged across all sites to establish a regional baseline. Fire intervals were also modeled in FHX2 using the Weibull distribution, which is a standard model for fire interval analysis (e.g. Sutherland 1997; Grissino-Mayer et al. 2004).

Geographic patterns of fire occurrence and intensity were then assessed. The percentage of stems scarred during any fire was divided into the following five classes: 0%; < 15%; 15-30%; 31-45%, and 45-60%. No fire year was represented by wounds on more than 60% of the trees within a site. Each site was then positioned on a GIS-derived regional map and site location markers were sized according to the scar percentage categories. Fire years that were detected on at least four of the study sites were displayed.

Finally, the Palmer Drought Severity Index (PDSI; Palmer 1965; Anon. 2006a) was used to compare climatic conditions in fire and non-fire years. Since practically all of the fire scars detected in our analysis occurred during the dormant season, the months March, April and May of the scarred year, and September, October and November of the previous year were used in the analyses. Comparisons were made between fire and non-fire years in two ways. First, mean PDSI during fire and non-fire years was compared (two-sided *t*-tests; Zar 1999) to test the hypothesis that fire occurred during periods of extended dry weather. Data were screened for normality prior to analysis using the D'Agostino omnibus test (D'Agostino et al. 1990). Second, χ^2-tests (Zar 1999) were used to test the hypothesis that fire years would occur when at least one month exhibited drought (PDSI value < –1). All tests were conducted using the statistical analysis software NCSS (Hintze 2001).

In order to account for possible inaccuracies in the assumption that fires occurred within the six months examined here, this set of monthly data was expanded (ultimately to include all months) and contracted (to include only September, October, March and April). These manipulations did not alter our conclusions. All climate data were downloaded from the National Climate Data Center CLIMVIS archive (Anon. 2006b). We used measured PDSI data (Kentucky Climate Division 3 and Ohio Climate Division 10) for the years 1895 to present (Anon. 2006b), and reconstructed PDSI values from gridpoint 228 (Kentucky) and gridpoint 236 (Ohio) for years prior to 1895 (Cook et al. 1999; Anon. 2006c).

Results

Samples were collected from a total of 225 trees in the nine study areas (Table 1; Fig. 1). The majority of samples were collected from *Quercus alba* (*n* = 114), with other samples coming from *Q. prinus* (*n* = 70), *Q. velutina* (*n* = 34), *Q. rubra* (*n* = 4), *Q. falcata* (*n* = 1), and two hickory (*Carya* spec.) stems not identified to species. Samples generally exhibited pith years from 1875 to 1925 and sample diameters ranged from 9.8 to 95.7 cm.

Fire wounding occurred almost exclusively during the dormant season and was recorded in relatively small stems. Scars from dormant-season fires, occurring after tree growth had ceased in the fall, but prior to the initiation of growth in the spring, were vastly more frequent (84% of fire events) than scars attributable to fires early in the growing season (13%). Scars caused by fires late in the growing season were rare (3%). Across sites, mean (± SE) basal diameter of stems at the time of fire scarring was 11.1 ± 1.5 cm.

Temporal patterns in historical fire occurrence

A period of frequent burning followed by a virtual absence of fire was noted in study sites across the region. For instance, in the Ohio BDS site, nine fire years were detected from 1878 to 1931 (Fig. 2). After 1931, wounds occurred but did not meet the minimum requirements for identification as a fire year. On the Ohio SHA site, fires were recorded throughout the period from 1889 to 1931 (Fig. 2). This period of frequent burning included nine fires, and no fires were detected after 1931 (Fig 2).

Forests in Kentucky exhibited a temporal pattern in historical fire that was similar to the Ohio sites. For instance, in the Kentucky DIC site, five fires were detected from 1893 to 1931, and a fire was recorded in 1954 (Fig. 3). Wounding occurred in the DIC site following the

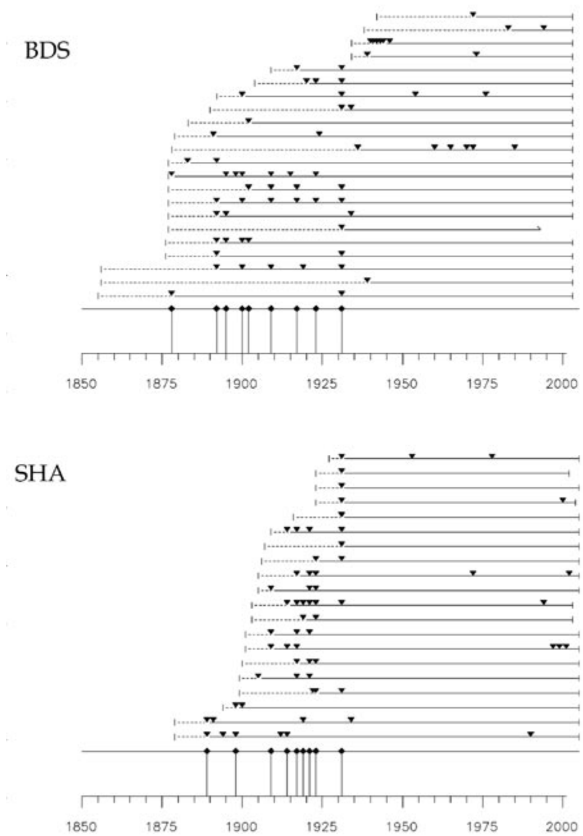

Fig. 2. Fire history diagrams from samples collected at two sites in southeastern Ohio. Within each panel, horizontal lines represent the growth years of an individual tree. Along each line, triangles indicate wound events. Lines are dotted prior to the occurrence of a wound event and solid afterward. A long, solid line at the bottom of the panel represents a composite upon which closed diamonds indicate a fire year (see text for composite line details). Lines connect these diamond markers to the chronology (at the bottom of the panel) indicating the fire year.

1954 fire, but the required landscape replication to be considered a fire was not met. In the Kentucky ROA site, eight fires occurred from 1885 to 1930. As was true of the DIC site, 1954 was a fire year in the ROA site, and no fires were detected after 1954 (Fig. 3).

Across the study region, fires occurred frequently from 1875 to 1936 and were virtually absent throughout the remainder of the chronology (Fig. 4). Mean fire return intervals in our study region ranged from 2.1 at EAG to 12.2 at DIC (Table 2). Weibull Median Interval was slightly lower than the mean return interval, ranging from 1.7 to 11.1 (Table 2). Across all sites, 7.1 ± 0.9 (mean ± SE) fires were detected and the Weibull Median Interval was 6.6 ± 1.0, with a minimum return of 2.4 ± 0.3 and a maximum return of 15.9 ± 2.1 (Table 2). This difference in minimum and maximum intervals suggests variability in fire return that was obvious in chronologies from across the region (Fig. 4). In many of the chronologies there was a period of frequent burning followed by 1-10 year absence and then a fire in 1931 (Fig. 4). Across all sites, only four fires were detected following 1936 (Fig. 4).

Spatial pattern in historical fire occurrence

Fire histories were similar across the 240-km latitudinal gradient included in our study and many fire years were identical across sites (Fig. 4). The fire years 1900, 1917, 1923 and 1931 were recorded on four or more sites (Fig. 5). Fires occurred on three of the Ohio sites in 1900 and fire was also detected (on more than 45% of the stems) in the southernmost Kentucky site (Fig. 5). The year 1917 was detected as a fire year on five of the Ohio sites, and one Kentucky site (Fig. 5). Fire occurred in four of the Ohio sites in 1923. Two Kentucky sites and all of the Ohio sites burned in 1931 (Fig. 5).

Relationship between climate and fire occurrence

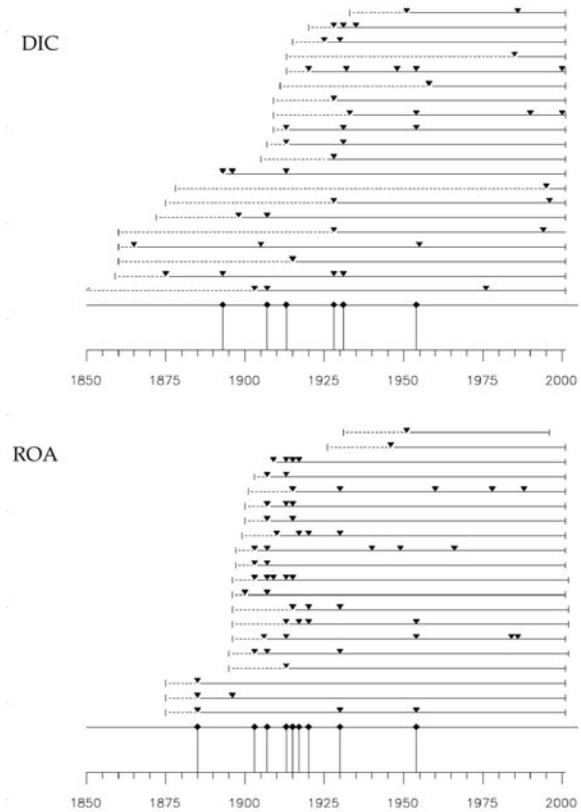

Fig. 3. Fire history diagrams from samples collected at two sites in eastern Kentucky. Within each panel, horizontal lines represent the growth years of an individual tree. Structure is the same as Fig. 2.

Table 2. Descriptive statistics for fire interval analysis of nine study sites in southeastern Ohio and eastern Kentucky, USA. Site details are available in Table 1. Sites are listed from left-to-right along a north-south gradient based on the location of the site. Intervals values are from the first fire year to the last fire year at each site. Last column is the mean of values on all sites. Note that since SIL had only two fires, the interval estimators could not be calculated.

Variable	EAG	WAT	BDS	ARC	RAC	SHA	ROA	DIC	SIL	Mean ± SE
Beginning year	1917	1875	1878	1900	1889	1889	1885	1893	1879	1889 ± 4.3
Ending year	1936	1934	1931	1936	1931	1931	1954	1954	1900	1934 ± 5.3
Fires	10.0	8.0	9.0	5.0	6.0	9.0	9.0	6.0	2.0	7.1 ± 0.9
Mean Interval (a)	2.1	8.4	6.6	9.0	6.4	5.3	8.6	12.2	*na*	7.3 ± 0.9
Median Interval	1.0	8.0	6.5	6.5	4.0	4.0	5.0	14.0	*na*	6.1 ± 1.4
MEI (a)	1.7	8.2	6.3	8.1	5.7	4.7	6.7	11.1	*na*	6.6 ± 1.0
MOI (a)	0.6	7.8	5.4	5.1	3.9	3.3	1.7	8.5	*na*	4.5 ± 1.0
Min. Interval	1.0	3.0	2.0	4.0	2.0	2.0	2.0	3.0	*na*	2.4 ± 0.3
Max. Interval	7.0	15.0	14.0	19.0	14.0	11.0	24.0	23.0	*na*	15.9 ± 2.1
CV	1.0	0.5	0.6	0.8	0.8	0.7	1.0	0.7	*na*	0.8 ± 0.1

Abbreviations: MEI = Weibull Median Interval; MOI = Weibull Modal Interval; CV = Coefficient of variation.

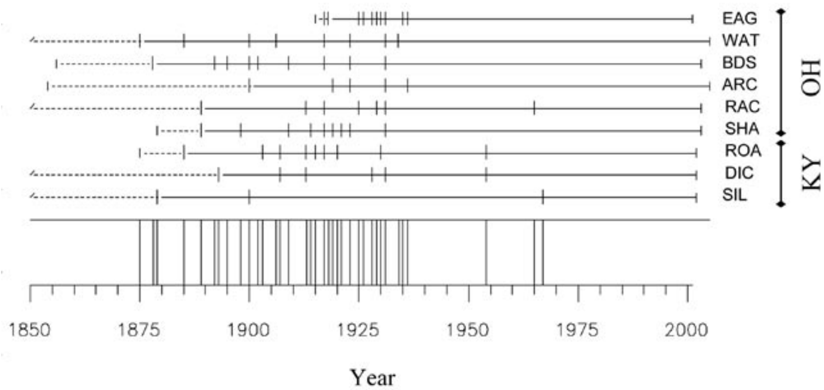

Fig. 4. Composite fire history diagram from nine oak forests in southeastern Ohio and eastern Kentucky, USA. Horizontal lines represent composite chronologies from each site (see text for composite details). These lines are organized from top-to-bottom along a north-to-south gradient based on the location of the site. Composite lines are secondarily grouped by state. Along each line, short vertical bars indicate fire years and lines are dotted prior to the occurrence of a fire year, and solid afterward. Vertical lines connected to a chronology (at the bottom of the panel) indicate that at least one of the sites exhibited a fire that year.

Fire occurrence was unrelated to drought occurrence, as Palmer Drought Severity Index (PDSI) values from fire and non-fire years were statistically indistinguishable (Kentucky, $P = 0.2$; Ohio $P = 0.4$). Association analysis (via χ^2) confirmed this result as fire occurrence and drought were not statistically associated for sites in either Ohio ($P = 0.4$) or Kentucky ($P = 0.3$). Fire years were recorded in a variety of climate conditions. Fire occurred during a period of drought from 1899 to 1905, and this drought period included the widespread fire year 1900 (Fig. 6). In contrast, fires were even more frequent during the period 1910 to 1925 even though this period

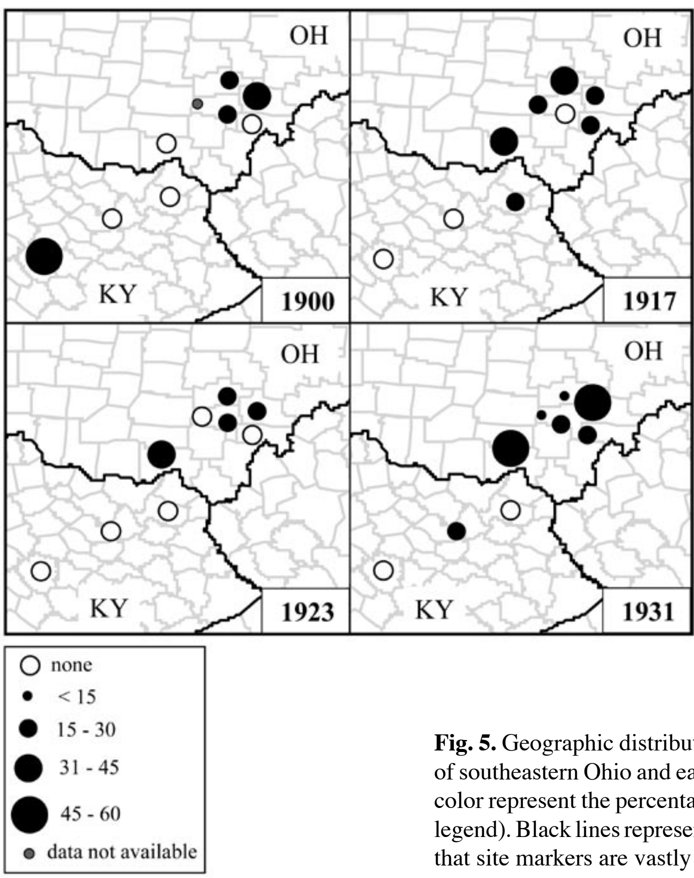

Fig. 5. Geographic distribution of the four most wide-spread fire years in oak forests of southeastern Ohio and eastern Kentucky. Dots indicate site locations. Dot size and color represent the percentage of stems scarred on that site during the given year (see legend). Black lines represent state boundaries, gray lines are county boundaries. Note that site markers are vastly larger than the actual size of the site.

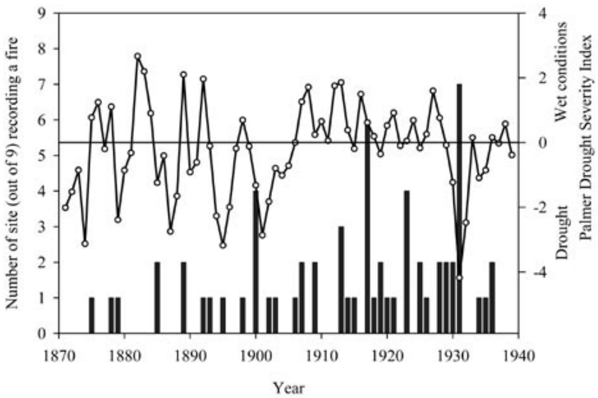

Fig. 6. Climate and fire occurrence in oak communities of southeastern Ohio and eastern Kentucky, USA. Histogram bars represent the number of sites (out of nine) where a fire was recorded, the line and scatter plot represents represent the mean of two regional PDSI measurement locations (see Text for details).

was characterized by wet climate conditions. In fact, two widespread fire years occurred during this period (1917 and 1923) were both 'normal' in terms of precipitation (Fig. 6). Notably, 1931 was the most widespread fire year in our sampling, and it was also the most extreme drought year during this time period (Fig. 6).

Discussion

Fire was a frequent occurrence during the establishment and early development of trees that comprise the current overstory in mixed-oak forests of our study area. Fires occurred approximately every 6-7 years during this period, with a minimum fire return interval of approximately every two years and a maximum interval of ca. 16 years. Fire may have been more frequent than these estimates suggest as McEwan et al. (in press) demonstrated that consecutive annual burns are likely to be undetected in oak fire scar chronologies. This period of frequent fire (ca. 1875 to 1936) was followed by a virtual absence of fire from ca. 1936 until the present. Similarly, the establishment and early development of trees comprising the current oak overstory in forests of western Maryland (Shumway et al. 2001) and elsewhere in Ohio (Sutherland 1997), coincided with frequent fire. Following ca. 1940, fire suppression activities, a publicity campaign against forest burning, and various land-use changes (alterations of settlement patterns, land abandonment, etc.) resulted in a reduction in fire frequency at a landscape level across much of North America (Oberle 1969; Dodge 1972; Pyne 1982; Abrams 1992).

Climate, regional fire occurrence, and Euro-American ignitions

In our study region, over the time period recorded by our samples, fires were frequent and widespread during both drought and wet climate conditions. This contrasts with many forests of western North America in which fire occurrence is strongly correlated with drought, while wet periods have resulted in an absence of fire (Veblen & Kitzberger 2002; Grissino-Mayer et al. 2004; Brown & Wu 2005). Forest fire occurrence is dependent upon fuel ignition, which occurs readily during drought and is unlikely during wet years when fuels are consistently damp. In mixed-oak forests, fires are carried primarily by leaf litter, which can dry enough for ignition and fire spread after only a few days of warm, dry and windy conditions. Fire ignition during these brief periods could quash any potential relationship between fire occurrence and climate as measured by monthly PDSI data.

In our study region, fires were detected during the same year across broad areas, including sites at the southernmost and northernmost extent of a 240-km latitudinal gradient during some years. This is a considerable distance since forested land in the study region was divided into small parcels, often bounded by features that would limit fire spread (e.g. roads, agricultural fields). Widespread fire in coniferous forests of western North America is often related to fire spreading through the landscape during extreme drought conditions (e.g. Brown et al. 1999; Grissino-Mayer et al. 2004). Synchronicity in fire occurrence in our study region was unrelated to climate, and occurred despite considerable barriers to fire spread. These facts strongly suggest that widespread fire years in our study region were caused by widespread ignitions and local spread rather than large fires moving through the landscape.

Euro-American cultural activities in the region may have been largely responsible for the fire regime present during the establishment (ca. 1870-1940) of the current overstory of mixed-oak forests of the study region. During this period, forest burning was a 'traditional' activity in some communities and was used to clear forest underbrush and to enhance opportunities for hunting (Pyne 1982). The most important sources of fire were probably sparks from locomotives and accidental ignitions associated with the timber industry (Pyne 1982; Brose et al. 2001). Frequent ignitions of anthropogenic origin have been recorded elsewhere in oak forests. Indeed, Guyette et al. (2002) identified an 'ignition saturated' phase in the fire history of oak forests in the Missouri Ozarks and suggest that Euro-American origin ignitions were so ubiquitous that fire was limited only by fuel exhaustion due to frequent burning. Further work is needed to determine if the Euro-American origin fire frequencies recorded in our study, and elsewhere, represent maximum values in the historical range of variability for these oak ecosystems (Brose et al. 2001; Guyette et al. 2002).

Historical fire and oak forest restoration

A lack of fire in the recent history of mixed-oak forests in eastern North America is thought to have caused diminished regeneration and recruitment of oaks and increased importance of maples (Abrams 1992; Van Lear & Watt 1993). Fire has been reintroduced in some oak forests to impede this successional dynamic (e.g. Chiang et al. 2005; Hutchinson et al. 2005), but the success of these efforts has been limited. In the short-term, prescribed fire has been successful at reducing the density of oak competitors in the sapling layer (e.g. Hutchinson et al. 2005); however, fire has most often been ineffective at increasing the abundance and size of oak regeneration relative to competitors (Albrecht & McCarthy 2006; Blankenship & Arthur 2006).

The success of prescribed fire experiments in modern oak forest may be improved by mimicking features of the fire regime present during the establishment of the current oak overstory in these forests (ca. 1870-1940). For instance, historical fires took place within forests that were regenerating following landscape-level deforestation during the late 1800s (Williams 1989; Whitney 1994). It is highly probable that an overstory canopy had not developed in many of these stands during the period of frequent fire. Due to the lack of an overstory canopy, selective mortality of relatively small stems during these fires may have increased light at the forest floor and facilitated oak regeneration and recruitment (Lorimer et al. 1994; Kruger & Reich 1997; Brose & Van Lear 1998). Prescribed fire experiments in recently harvested and regenerating stands may provide insight into the oak-fire relationship.

The duration of frequent fire is another important, and potentially applicable, feature of the historical regime. Fire occurred in our sites over a period of at least 60 years. This duration of frequent fire is far longer than that of prescribed burning in most oak forests (Hutchinson et al. 2005; Albrecht & McCarthy 2006; Blankenship & Arthur 2006). It is likely that 60 years of frequent, repeated, burning would have a substantially different ecological effect than that achievable with only a few fires (Harrod et al. 2000). Experiments seeking to mimic conditions present during the initiation of modern mixed-oak forests should apply prescribed fire consistently over several decades.

The temporal pattern of fire occurrence within sites was irregular, and fires occurred during a variety of climatic conditions. All of the stands in our study exhibited large differences between the minimum and maximum fire return, and most of the stands exhibit periods of frequent fire, followed by lags and then subsequent burning. This variability in the fire regime may have influenced the competitive balance between oaks and maples. Fires also occurred during a variety of climatic conditions. This variability in climate likely created variability in fire intensity and, thus, variability in ecological effect. In particular, burning during extreme drought may have caused substantial tree mortality increasing light at the forest floor. Experimental prescribed fire regimes could include frequent burning followed by lags, which would better mimic historical variability in fire occurrence. These activities could also mimic historical fires by applying prescribed fire under a variety of moisture conditions.

Conclusions

Fire was a wide-spread and frequent occurrence during the establishment and development of the current overstory in mixed-oak forests in our study region. In the recent past (ca. 1870 to present) this process was temporally biphasic; frequent fires occurred from 1870 to 1940 after which fire was practically absent from the landscape. During the period of frequent burning, fire was geographically widespread, sometimes occurring at the extremes of a 240-km gradient during the same year. There was within-site temporal variability of fire occurrence— frequent fires, followed by lags, then more fires. Burning occurred in a variety of climate conditions including both wet years and extreme drought. In sum, a suite of process characteristics can be discerned from the historical fire record. Attempts to mimic these conditions when applying prescribed fire as a restoration treatment in modern stands may increase the likelihood that the restoration treatment will produce the desired ecological result.

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References

Anon. 2005. FHX2 software. Forest Research Tools URL: http://www.forestresearchtools.com [Cited 21.03.2005.]

Anon. 2006a. *Palmer Drought Severity Index Explanation*. URL: http://www.drought.noaa.gov/palmer.html [Cited 10.04.2006.]

Anon. 2006b. *Palmer Drought Severity Index*. National Climate Data Center (NCDC) CLIMVIS Archive. (Kentucky Division 3 - Ohio Division 10). URL: http://www.ncdc. noaa. gov/oa/climate/onlineprod/drought/xmgr.html#. [Cited 10.04.2006.]

Anon. 2006c. National Climate Data Center (NCDC) Paleoclimatology Archive (Ohio Gridpoint 236 - Kentucky Gridpoint 228). URL: http://www.ncdc.noaa.gov/paleo/newpdsi.html. [Cited 26.07.2006.]

Abrams, M.D. 1992. Fire and the development of oak forests. *BioScience* 42: 346-353.

Albrecht, M.A. & McCarthy, B.C. 2006. Effects of prescribed fire and thinning on tree recruitment patterns in central hardwood forests. *For. Ecol. Manage*. 226: 88-103.

Anderson, R.C. & Brown, L.E. 1983. Comparative effects of fire on trees in a midwestern savannah and an adjacent forest. *Bull. Torrey Bot. Club* 110: 87-90.

Arthur, M.A., Paratley, R.D. & Blankenship, B.A. 1998. Single and repeated fires affect survival and regeneration of woody and herbaceous species in an oak-pine forest. *J. Torrey Bot. Soc*. 125: 225-236.

Blankenship, B.A. & Arthur, M.A. 2006. Stand structure over 9 years in burned and fire-excluded oak stands on the Cumberland Plateau, Kentucky. *For. Ecol. Manage*. 255: 134-145.

Braun, E.L. 1950. *Deciduous forests of eastern North America*. Blakiston, Philadelphia, PA, US.

Brose, P.H. & Van Lear, D.H. 1998. Responses of hardwood advance regeneration to seasonal prescribed fires in oak-dominated shelterwood stands. *Can. J. For. Res*. 28: 331-339.

Brose, P.H. & Waldrop, T.A. 2006. Fire and the origin of Table Mountain pine - pitch pine communities in the southern Appalachian Mountains, USA. *Can. J. For. Res*. 36: 710-718.

Brose, P.H., Schuler, T. & Van Lear, D. 2001. Bringing fire back, The changing fire regimes of Appalachian mixed-oak forests. *J. For.* 99: 30-35.

Brown, P.M. 2006. Climate effects on fire regimes and tree recruitment in Black Hills ponderosa pine forests. *Ecology* 87: 2500-2510.

Brown, P.M. & Wu, R. 2005. Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. *Ecology* 86: 3030-3038.

Brown, P.M., Kaufmann, M.R. & Shepperd, W.D. 1999. Long-term landscape patterns of past fire events in a mountain ponderosa pine forest of central Colorado. *Landscape Ecol*. 14: 512-532.

Chiang, J.M., Arthur, M.A. & Blankenship, B.A. 2005. The effect of prescribed fire on gap fraction in an oak forest understory on the Cumberland Plateau. *J. Torrey Bot. Soc*. 132: 432-441.

Christensen, N.L. 1993. Fire regimes and ecosystem dynamics. In: Crutzen, P.J. & Goldammer, J.G. (eds.) *Fire in the environment: The ecological, atmospheric, and climatic importance of vegetation fires*, pp 234-244. John Wiley and Sons, Hoboken, NJ, US.

Cook, E.R., Meko, D.M., Stahle, D.W. & Cleaveland, M.K. 1999. Drought reconstructions for the continental United States. *J. Climate* 12: 1145-1162.

Crow, T.R. 1988. Reproductive mode and mechanisms for self-replacement of northern red oak (*Quercus rubra*) – A review. *For. Sci*. 34: 19-40.

Cutter, B.E. & Guyette, R.P. 1994. Fire frequency on an oak-hickory ridgetop in the Missouri Ozarks. *Am. Midl. Nat*. 132: 393-398.

D'Agostino, R.B., Belanger, A. & D'Agostino Jr., R.B. 1990. A suggestion for using powerful and informative tests of normality. *Am. Stat*. 44: 316-321.

Delcourt, P.A., Delcourt, H.A., Ison, C.R., Sharp, W.E. & Gremillion, K.J. 1998. Prehistoric human use of fire, the eastern agricultural complex, and Appalachian oak-chestnut forests: paleoecology of Cliff Palace Pond, Kentucky. *Am. Antiquity* 63: 263-278.

Denevan, W.M. 1992. The pristine myth: The landscape of the Americas in 1492. *Ann. Ass. Am. Geogr.* 82: 369-385.

Dodge, M. 1972. Forest fuel accumulation – A growing problem. *Science* 177: 139-142.

Dyer, J.M. 2001. Using witness trees to assess forest change in southeastern Ohio. *Can. J. For. Res*. 31: 1708-1718.

Dyer, J.M. 2006. Revisiting the deciduous forests of eastern North America. *BioScience* 56: 341-352.

Egan, D. & Howell, E.A. 2001. *The historical ecology handbook*. Island Press, Washington, DC, US

Fulé, P.Z., Heinlein, T.A., Covington, W.W. & Moore, M.M. 2003. Assessing fire regimes on Grand Canyon landscapes with fire-scar and fire-record data. *Int. J. Wildland Fire* 12: 129-145.

Gleason, H.A. & Cronquist, A. 1991. *Manual of vascular plants of northeastern United States and adjacent Canada*. New York Botanical Garden, Bronx, NY, US.

Goebel, P.C. & Hix, D.M. 1996. Development of mixed-oak forests in southeastern Ohio: a comparison of second-growth and old-growth forests. *For. Ecol. Manage*. 84: 1-21.

Grissino-Mayer, H.D. 2001. FHX2-Software for analyzing temporal and spatial patterns in fire regimes from tree rings. *Tree-ring Res*. 57: 115-121.

Grissino-Mayer, H.D. & Swetnam, T.W. 2000. Century-scale climate forcing of fire regimes in the American Southwest. *The Holocene* 10: 213-220.

Grissino-Mayer, H.D., Romme, W.H., Floyd, M.L. & Hanna, D.D. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. *Ecology* 85: 1708-1724.

Guyette, R.P. & Spetich, M.A. 2003. Fire history of oak-pine forests in the Lower Boston Mountains, Arkansas, USA. *For. Ecol. Manage*. 180: 463-474.

Guyette, R.P., Muzika, R.M. & Dey, D.C. 2002. Dynamics of an anthropogenic fire regime. *Ecosystems* 5: 472-486.

Harrod, J.C., Harmon, M.E. & White, P.S. 2000. Post-fire succession and 20th century reduction in fire frequency on xeric southen Appalachian sites. *J. Veg. Sci*. 11: 465-472.

Hintze, J. 2001. *NCSS and PASS*. Number Cruncher Statistical

Systems. Kaysville, UT, US.
Hutchinson, T.F., Rubino, D., McCarthy, B.C. & Sutherland, E.K. 2003. History of forests and land-use. In: Sutherland E.K. & Hutchinson, T.F. (eds.) *Characteristics of mixed-oak forest ecosystems in southern Ohio prior to the reintroduction of fire,* pp 17-27. USDA Forest Service, Gen. Tech. Rep. NE-299. Northeastern Research Station, Newtown Square, PA, US.
Hutchinson, T.F., Sutherland, E.K. & Yaussy, D.A. 2005. Effects of prescribed fires on the structure, composition and regeneration of mixed-oak forests in Ohio. *For. Ecol. Manage*. 218: 210-228.
Kruger, E.L. & Reich, P.B. 1997. Responses of hardwood regeneration to fire in mesic forest openings. I. Post-fire community dynamics. *Can. J. For. Res*. 27: 1822-1831.
Lafon, C.W., Hoss, J.A. & Grissino-Mayer, H.D. 2005. The contemporary fire regime of the central Appalachian Mountains and its relation to climate. *Phys. Geogr.* 26: 126-146.
Lorimer, C.G. 1984. Development of the red maple understory in northeastern oak forests. *For. Sci*. 30; 3-22.
Lorimer, C.G., Chapman, J.W. & Lambert, W.D. 1994. Tall understorey vegetation as a factor in the poor development of oak seedlings beneath mature stands. *J. Ecol*. 82: 227-237.
McCarthy, B.C., Hammer, C.A., Kauffman, G.L. & Cantino, P.D. 1987. Vegetation patterns and structure of an old-growth forest in southeastern Ohio. *Bull. Torrey Bot. Club* 114: 33-45.
McCarthy, B.C., Small, C.J. & Rubino, D.L. 2001. Composition, structure and dynamics of Dysart Woods, an old-growth mixed mesophytic forest of southeastern Ohio. *For. Ecol. Manage*. 140: 193-213.
McCormick, J.F. & Platt, R.B. 1980. Recovery of an Appalachian forest following the chestnut blight. *Am. Midl. Nat*. 104: 264-273.
McEwan, R.W. & Muller, R.N. 2006. Spatial and temporal dynamics in canopy dominance of an old-growth mixed mesophytic forest. *Can. J. For. Res*. 36: 1536-1550.
McEwan, R.W., Muller, R.N. & McCarthy, B.C. 2005. Vegetation-environment relationships among four canopy-layers in an old-growth mixed mesophytic forest. *Castanea* 70: 32-46.
McEwan, R.W., Hutchinson, T.F., Ford, R.D. & McCarthy, B.C. In press. An experimental evaluation of fire history reconstruction using dendrochronology in white oak. *Can. J. For. Res.*
Moore, M.M., Covington, W.W. & Fulé, P.Z. 1999. Reference conditions and ecological restoration: A southwestern Ponderosa Pine perspective. *Ecol. Appl*. 9: 1266-1277.
Muller, R.N. 1982. Vegetation patterns in the mixed mesophtyic forest of eastern Kentucky. *Ecology* 63: 1901-1917.
Oberle, M. 1969. Forest fires: Suppression policy has its ecological drawbacks. *Science* 165: 568-571.
Palmer, W.C. 1965. *Meteorological drought*. Research Paper No. 45, Department of Commerce, Washington, DC, US.
Pyne, S.J. 1982. *Fire in America*. University of Washington Press, Seattle, WA, US.
Schuler, T.M. & McClain, W.R. 2003. *Fire history of a ridge and valley oak forest.* Res. Pap. NE-724. USDA Forest Service, Northeastern Research Station. Newtown Square, PA, US.
Shumway, D.L., Abrams, M.D. & Ruffner, C.M. 2001. A 400-year history of fire and oak recruitment in an old-growth forest in western Maryland, U.S.A. *Can. J. For. Res*. 31: 1437-1443.
Soucy, R.D., Heitzman, E. & Spetich, M.A. 2005. The establishment and development of oak forests in the Ozark Moutains of Arkansas. *Can. J. For. Res*. 35: 1790-1797.
Stokes, M.A. & Smiley, T.L. 1968. An introduction to tree-ring dating. The University of Arizona Press, Tucson, AZ, US.
Stout, W. 1933. The charcoal iron industry of the hanging rock iron district – Its influence on the early development of the Ohio Valley. *Ohio Archaeol. Hist. Quart*. 42: 72-104.
Sutherland, E.K. 1997. History of fire in a southern Ohio second-growth forest. In: Pallardy, S.G., Cecich, R.A., Garrett, H.E. & Johnson, P.S. (eds) *11th Central Hardwood Forest Conference*, pp 172-183. USDA Forest Service, Gen. Tech. Rep. NC-188. North Central Forest Experiment Station, St. Paul, MN, US.
Sutherland, E.K. & Hutchinson, T.F. 2003. *Characteristics of mixed-oak forest ecosystems in southern Ohio prior to the reintroduction of fire*. USDA Forest Service, Gen. Tech. Rep. NE-299. Northeastern Research Station, Newtown Square, PA, US.
Swetnam, T.W., Allen, C.D. & Betancourt, J.L. 1999. Applied historical ecology: Using the past to manage for the future. *Ecol. Appl*. 9: 1189-1206.
Trammell, T.L.E., Rhoades, C.C. & Bukaveckas, P.A. 2004. Effects of prescribed fire on nutrient pools and losses from glades occurring within oak-hickory forests of central Kentucky. *Rest. Ecol*. 12: 597-604.
Van Horne, M.L. & Fulé, P.Z. 2006. Comparing methods of reconstructing fire history using fire scars in a southwestern United States ponderosa pine forest. *Can. J. For. Res*. 36: 855-867.
Van Lear, D.H. & Watt, J.M. 1993. The role of fire in oak regeneration. In: Loftis, D. & McGee, C.E. (eds.) *Oak regeneration: Serious problems, practical recommendations*, pp. 66-78. USDA Forest Service, Gen. Tech. Rep. SE-84. Southeastern Research Station, Asheville, NC, US.
Veblen, T.T. & Kitzberger, T. 2002. Interhemispheric comparison of fire history: The Colorado Front Range, USA and the Northern Patagonian Andes, Argentina. *Plant Ecol*. 163: 187-207.
Walker, J.E. 1983. The travel notes of Joseph Gibbons, 1804. *Ohio History* 92: 96-146.
Wan, S., Hui, D. & Luo, Y. 2001. Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: A meta-analysis. *Ecol. Appl*. 11: 1349-1365.
Whitney, G.G. 1994. *From coastal wilderness to fruited plain*. Cambridge University Press, New York, NY, US.
Williams, M. 1989. *Americans and their forests: a historical geo-graphy*. Cambridge University Press, New York, NY, US.
Zar, J.H. 1999. *Biostatistical analysis*. Prentice Hall, Upper Saddle River, NJ, US.

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