

Fire history and the establishment of oaks and maples in second-growth forests

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Abstract: We used dendrochronology to examine the influence of past fires on oak and maple establishment. Six study units were located in southern Ohio, where organized fire control began in 1923. After stand thinning in 2000, we collected basal cross sections from cut stumps of oak ($n = 137$) and maple ($n = 204$). The fire history of each unit was developed from the oaks, and both oak and maple establishment were examined in relation to fire history. Twenty-six fires were documented from 1870 to 1933; thereafter, only two fires were identified. Weibull median fire-return intervals ranged from 9.1 to 11.3 years for the period ending 1935; mean fire occurrence probabilities (years/fires) for the same period ranged from 11.6 to 30.7 years. Among units, stand initiation began ca. 1845 to 1900, and virtually no oak recruitment was recorded after 1925. Most maples established after the cessation of fires. In several units, the last significant fire was followed immediately by a large pulse of maple establishment and the cessation of oak recruitment, indicating a direct relationship between fire cessation and a shift from oak to maple establishment.

Résumé : Nous avons eu recours à la dendrochronologie pour étudier l'influence du feu dans le passé sur l'établissement du chêne et de l'érable. Six unités expérimentales ont été localisées dans le sud de l'Ohio où la lutte organisée contre les feux a débuté en 1923. Après que des peuplements eurent été éclaircis en 2000, nous avons collecté des sections radiales sur des souches de chêne ($n = 137$) et d'érable ($n = 204$). Dans chaque unité, l'historique des feux a été établi à partir des chênes et l'établissement du chêne et de l'érable a été étudié en lien avec l'historique des feux. Vingt-six feux ont été documentés de 1870 à 1933; par la suite, seulement deux feux ont été identifiés. L'intervalle médian de Weibull entre les feux variait de 9,1 à 11,3 ans pour la période se terminant en 1935; la probabilité moyenne d'occurrence de feux (années/feux) pendant la même période variait de 11,6 à 30,7 ans. Parmi les unités, l'origine des peuplements remonte aux environs de 1845 à 1900 et pratiquement aucun chêne n'a été recruté après 1925. La plupart des érables se sont établis après que les feux eurent cessé. Dans plusieurs unités, le dernier feu important a immédiatement été suivi d'une importante vague d'établissement de l'érable et de l'arrêt du recrutement du chêne, indiquant qu'il y a une relation directe entre la cessation des feux et le changement marqué par l'établissement de l'érable au lieu du chêne.

[Traduit par la Rédaction]

Introduction

Across much of the eastern United States, red maple (*Acer rubrum* L.), sugar maple (*Acer saccharum* Marsh.), and other mesophytic and (or) shade-tolerant species have become abundant in historically oak-dominated landscapes, threatening the continued dominance of oak (Lorimer 1984; Abrams 1992). Fire-control policies instituted ca. 1910 to 1930 often are considered a primary cause of these successional trends (e.g., Lorimer 1993).

Oaks are considered to be better adapted than maples to a regime of periodic fires primarily because of their relatively thick and, thus, fire-resistant bark; their ability to compartmentalize wounds caused by fire; and the capacity of established seedlings to continue to sprout after being top-killed repeatedly (Smith and Sutherland 1999; Johnson et al. 2002; Van Lear and Brose 2002). Periodic anthropogenic fire is

widely considered to have promoted and sustained eastern oak ecosystems throughout their postglacial history (Abrams 2002). However, specific knowledge of past fire regimes, which can be obtained by analysis of fire-scarred trees, is limited to relatively few areas. Several studies show that fire was frequent in oak ecosystems prior to (Cutter and Guyette 1994; Guyette et al. 2003; Shumway et al. 2001) and after Euro-American settlement (Sutherland 1997; Schuler and McClain 2003; Guyette and Stambaugh 2004; Soucy et al. 2005) until fire control was instituted.

Much more is known about long-term patterns of tree establishment in old-growth oak forests. These studies often suggest a strong influence of fire cessation on tree recruitment (e.g., Abrams and Downs 1990; Abrams and Copenhaver 1999; Aldrich et al. 2005). Oak recruitment is known to have occurred for up to several hundred years but

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decreased or ceased around the time that fire control began. Several of these studies also document greatly increased recruitment of maples and other nonoak species during the same period (e.g., Abrams and Downs 1990; Abrams and Copenheaver 1999).

Shumway et al. (2001) were the first to document both the fire history and patterns of establishment for oak and other species in an old-growth oak-dominated stand in western Maryland. The authors showed that fire and oak recruitment were frequent from the early 1600s through the early 1900s. Both the cessation of oak recruitment and the increased recruitment of red maple and black birch (*Betula lenta* L.) coincided with reduced fire frequency ca. 1930. Soucy et al. (2005) showed that oak–hickory stands in the Arkansas Ozarks originated following harvesting or fire ca. 1900 and that fires were frequent through the 1930s. As fires became much less frequent after ca. 1940, oak recruitment ceased, and other shade-tolerant, nonoak species, such as flowering dogwood (*Cornus florida* L.), red maple, and blackgum (*Nyssa sylvatica* Marsh.), became established (Soucy et al. 2005).

The unglaciated “hill country” of southeastern Ohio was dominated by oak forests ca. 1800, just prior to Euro-American settlement (Beatley 1959; Gordon 1969; Dyer 2001). After nearly all of the forests in the region were cut over in the 19th century, many stands regenerated to oak dominance (Goebel and Hix 1997; Dyer 2001; Yaussy et al. 2003), and oak remains abundant in the region today (Griffith et al. 1993). However, as with most areas in the eastern United States that historically were oak dominated, the continued abundance of oak is threatened by increasing densities of maples and other species (e.g., blackgum and beech (*Fagus grandifolia* Ehrh.)) and poor oak regeneration. Dendrochronology fire histories indicate that fires occurred frequently in the region from ca. 1870 to 1935 (Sutherland 1997; McEwan et al. 2007b). It is hypothesized that this fire regime sustained oak dominance as second-growth forests developed (McEwan et al. 2007b) and that fire control directly facilitated the establishment of the now-abundant maples and other competitors (Sutherland et al. 2003).

To better understand how past fires were related to tree establishment, we conducted a dendrochronology study at the Ohio Hills site of the national Fire and Fire Surrogate Study (FFS). Our study was carried out on three replicate sites, each containing two separate units (~20 ha each) that were thinned. The second-growth forests were dominated by oak in the overstory, but maples and other shade-tolerant species were abundant in the midstory and understory. We collected basal cross sections from cut stumps of both oaks and maples to document stand fire histories and tree establishment. We hypothesized that, within a stand, temporal patterns of oak and maple recruitment would be closely related to the occurrence of past fires. Specifically, we hypothesized that (i) fires were frequent prior to the initiation of fire control, (ii) oak establishment occurred primarily before the initiation of fire control, and (iii) maples established primarily during the fire-control era. By studying units within three spatially separated replicate sites that likely had different fire histories, we also hoped to better understand how variability in past fire regimes affected oak and maple establishment. To our knowledge, this is the first

study that directly examines the relationship between specific historic fire events and oak and maple recruitment events. A better understanding of how past fire regimes affected the pattern and pace of recruitment during stand development could provide new insights for the use of prescribed fire to manage oak forests.

Methods

Study area and site descriptions

The study area is in southern Ohio within the Southern Unglaciated Allegheny Plateau (McNab and Avers 1994). The topography is highly dissected, consisting of sharp ridges, steep slopes, and narrow valleys. The bedrock geology is predominantly sandstones and shales that produce well-drained and acidic soils.

The Ohio Hills FFS study site has three replicates (hereafter sites): one each in the Raccoon Ecological Management Area (REMA), Zaleski State Forest, and Tar Hollow State Forest. The REMA site (39°12'34"N, 82°23'07"W) is in Vinton County and within the Vinton Furnace Experimental Forest; owned by Forestland Group, LLC, and co-managed with the USDA Forest Service Northern Research Station. The Zaleski site (39°21'22"N, 82°21'59"W), also in Vinton County, is 19 km north of the REMA site. The Tar Hollow site (39°19' 47"N, 82°46'11"W) is in Ross County, 35 km west of the Zaleski site. Soils at both REMA and Zaleski are predominantly Steinsburg and Gilpin series silt loams (Typic Hapludalfs); Tar Hollow soils are predominantly Shelocta–Brownsville complex sandy loams (Typic Hapludalfs and Typic Dystrochrepts, respectively) (Boerner et al. 2007). Both state forests are managed by the Ohio Department of Natural Resources' (ODNR) Division of Forestry.

Human land use has had a major effect on these forests. Both the REMA and Zaleski sites are located near charcoal iron furnaces that operated in the 1800s. REMA is <2 km from Vinton Furnace and Zaleski is <4 km from Hope Furnace; these were in operation from 1853 to 1883 and from 1854 to 1874, respectively (Stout 1933). Forests at both sites presumably were harvested at least once to provide charcoal for iron smelting. The Tar Hollow site was not affected by the iron industry since it was more than 25 km from the nearest furnace. Land deeds show direct human occupation in small parcels within the Tar Hollow study site until the mid-1930s (ODNR, Division of Forestry, District Office, Chillicothe, Ohio).

The forests generally were similar in structure and composition across the three sites. Prethinning data collected in 2000 showed that mean stand basal area at REMA was 28 m²/ha; white oak (*Quercus alba* L.) accounted for 21% of the basal area; black oak (*Quercus velutina* Lam.), 17%; chestnut oak (*Quercus montana* Willd.), 15%; and scarlet oak (*Quercus coccinea* Muenchh.), 12% (D.A. Yaussy, USDA Forest Service, Delaware, Ohio, unpublished data). Mean basal area at Zaleski was 27 m²/ha and was dominated by chestnut oak (31%), followed by white oak (22%), red maple (13%), and black oak (13%). At Tar Hollow, mean basal area was 32 m²/ha, and the dominant species were chestnut oak (33%), white oak (20%), and black oak (16%). Oak site indices (base age 50 years) are variable across the

landscape because of the dissected topography, ranging from about 17 m (55 ft) on upper south-facing slopes to 24 m (80 ft) on lower north-facing slopes (D.A. Yaussy, USDA Forest Service, Delaware, Ohio, personal communication). On all sites, the sapling layer (1.4 m tall to 9.9 cm diameter at breast height (DBH)) and the midstory (trees 10–25 cm DBH) were dominated by shade-tolerant trees, the most abundant of which were red maple, sugar maple, blackgum, and beech (Albrecht and McCarthy 2006). Shade-tolerant trees >25 cm DBH occurred at low densities on all sites.

The mean annual temperature and precipitation are 11.3 °C and 1024 mm, respectively. Precipitation is distributed fairly evenly throughout the year with no months averaging <60 mm. Today, most fires occur during the early spring (March and April) and fall (October and November), when vegetation is predominantly dormant; spring dormant-season fires are the most frequent (Haines et al. 1975; Sutherland et al. 2003), and nearly all fires are anthropogenic in origin.

At each FFS site, four treatment units (19–26 ha) were established: an untreated control (control), mechanical thinning (thin), prescribed fire (burn), and a combination of thinning and fire (thin+burn). Our dendrochronology study was conducted on the two thinned units (thin and thin+burn) at each site. Midstory thinning occurred from November 2000 to April 2001 and favored the retention of dominant and codominant oaks. However, to meet commercial thinning objectives, some dominant and codominant oaks were harvested. Across sites, stand density (trees ≥ 10 cm DBH) was reduced by 32% from a mean of 400 to 269 trees/ha, and tree basal area was reduced by 30% from a mean of 29 to 20 m²/ha.

Sampling design and field methods

At the REMA site, the two thinned units (hereafter, REMA 2 and REMA 3) were separated by a triangular wedge of untreated forest that ranged in width from several meters to 275 m. The Zaleski thinned units (Zaleski 2 and Zaleski 3) were contiguous, and the boundary between units was an intermittent stream drainage. The Tar Hollow thinned units (Tar Hollow 2 and Tar Hollow 3) also were contiguous, but the boundary did not follow a major topographic feature. Despite the contiguous units at Zaleski and Tar Hollow, we treated the units separately for summary and analyses, because 50% (14 of 28) of the fires that we documented were recorded only in a single unit.

Ten 0.1 ha plots were established in each unit to monitor vegetation and soils for the FFS study. Plot corners were georeferenced with global positioning system (GPS) technology. The plots were distributed across the landscape to represent a continuous range of soil moisture conditions from dry (upper south-facing slopes) to mesic (lower north-facing slopes). In 2000, all overstory trees (≥ 10 cm DBH) were tallied by species and DBH on each plot prior to treatments. We focused our collection of oak and maple basal cross sections on the plots to utilize the tree data and georeferenced locations.

Full basal cross sections were cut from stumps with a chainsaw from December 2000 to May 2001, soon after thinning operations had been completed in each unit. All oak stumps in a plot were examined for the presence of wounds (discoloration, seams, staining, and wound wood ribs) that might indicate a fire event (Smith and Sutherland

1999). We attempted to locate at least two oak stumps within or adjacent to each plot. We collected 137 oak cross sections across all units and recorded the upslope position on each. Samples included 64 white oak, 40 chestnut oak, 22 black oak, 7 scarlet oak, and 4 northern red oak (*Quercus rubra* L.). All samples were cut at a height of about 5–10 cm aboveground. The mean basal diameter of the oak samples was 47.4 cm and ranged from 23.1 to 98.1 cm. We mapped the approximate location of each sample based on its position within or adjacent to a georeferenced vegetation plot.

To determine the temporal pattern of maple establishment, our objective was to collect basal cross sections from three stumps in and (or) adjacent to each plot. Our goal was to collect three maples for every two oaks, because maples were approximately 1.5 times as abundant as oaks in the midstory, where the thinning treatment was focused. Our first priority was to obtain larger maples to document the time when establishment began, but we sampled across a range of maple stump diameters. We collected 30–39 maples per unit for a total of 204 (142 red maple and 62 sugar maple). Nearly all sugar maple samples were collected in three units: Tar Hollow 2 ($n = 27$), Tar Hollow 3 ($n = 20$), and REMA 3 ($n = 15$). The mean basal diameter of maple samples was 27.5 cm and ranged from 10.1 to 58.4 cm.

Laboratory methods

Cross sections were planed and sanded to enhance ring boundaries and facilitate dating. Each oak sample was cross-dated using skeleton plots (Stokes and Smiley 1968) against a previously established master chronology for the region (Sutherland 1997). Maple cross sections ≥ 70 years old also were skeleton plotted and cross-dated. Younger maple samples were ring-counted along two to four radii and cross-dated by identification of key stress years. Several factors contributed to make the exact pith dates for maples somewhat less precise than that for the oaks. Firstly, the cross-dating was less clear for maples than for the oaks, i.e., key stress years were not as consistent among the maples. Secondly, a small proportion of the maples had decay or incipient decay in or near the pith, which obscured the ring boundaries. Thirdly, some maples had rings that were locally absent in a portion of their circumference, a common phenomenon documented by Lorimer et al. (1999) for suppressed sugar maple trees. Several samples that we felt could not be reliably dated (primarily small suppressed stems) were omitted from further analyses.

We required at least three scarred samples per unit per year to classify a wound event as a fire scar and, consequently, a year as a fire year. If only two wounds were present in a unit in a given year but the adjacent unit showed evidence of a fire in the same year (three or more samples scarred), we recorded a fire for the unit with only two scars (this occurred once). These criteria were applied to limit the likelihood that wounds caused by other factors (e.g., logging, falling trees and branches, or animals) were recorded as fire scars (see McEwan et al. 2007a). The seasonality of each fire event was determined by examining where the wounds intersected the annual growth ring. For dormant-season scars (located between annual growth rings) it was not possible to determine whether the scar occurred in the fall after the previous growing season or in the late

winter–early spring prior to the upcoming growing season (Sutherland 1997). Because fires in our region are most frequent in the early spring dormant season (March–April), we assigned dormant-season wounds to the calendar year of the upcoming growing season. For example, a dormant-season wound located between the 1922 and 1923 annual growth rings was recorded as a 1923 wound.

To better examine how the relative intensity and (or) extent of fires may have affected tree establishment, we defined fires as “significant” if (i) $\geq 33.3\%$ of the samples exhibited wounds and (ii) at least five samples had wounds. Since little is known about the relationship between fire intensity and scarring in oaks (see Smith and Sutherland 1999; Guyette and Stambaugh 2004; McEwan et al. 2007a), this definition provides a relative measure of the intensity and extent of the fires within this study.

We mapped the location of all samples (oaks and maples) in all fire years at REMA to visualize the spatial pattern of fire scars and tree establishment across the landscape. We used the ArcView version 3.2a geographic information system to map samples based on our field maps that showed locations within or adjacent to a georeferenced vegetation plot. We selected eight of the nine fire years at the REMA study site to illustrate spatial patterns of fire scarring and tree establishment.

Ring widths were measured on the oaks so that growth dynamics and potential release events could be determined. Oak cross sections were scanned and measured using WINDENDRO (Regent Instruments Inc., Ste-Foy, Que.). Two radii approximately 180° apart were measured in each cross section. Radii were located to minimize the influence of wounds and associated wound wood on growth measurements. Ring-width measurements and cross-dating were verified with the program COFECHA 2.1 (Holmes 1983; Grissino-Mayer 2001b). The program ARSTAN (Cook and Kairiukstis 1990) from the Lamont Doherty Earth Observatory’s Tree-Ring Laboratory, was used to detrend measurements with a negative exponential curve or linear regression line. This standardization procedure removes the growth trend associated with age and produces dimensionless indices that can be averaged to create a master chronology for a site (Fritts 1976). A master chronology was created for each of the six sampled sites.

Potential releases associated with disturbance events were identified in each master chronology with the JOLTS program (Holmes 1999) from the International Tree-Ring Data Bank Dendrochronology Program Library. Major releases were those where there was a $>100\%$ increase in growth expressed as the mean chronology ring-width index over a 15 year period compared with the mean chronology ring-width index in the preceding 15 year period. Minor releases were those where growth increased 50% over a 10 year period compared with a previous 10 year period (Lorimer and Frelich 1989; Soucy et al. 2005). We report release events only when there were at least 10 trees present in the master chronology.

Fire-return interval analyses

Data on fire history derived from oak cross sections were analyzed using the FHX2 program (Grissino-Mayer 2001a, 2004). Because fires were so infrequent after 1935, it was

not possible to statistically compare fire frequency between pre- and post-fire suppression periods. Instead, for each study unit, we calculated fire intervals from the first fire to 1935 (before and during the early fire-control period) and compared these with fire intervals from the first fire to 2000. Both mean fire intervals (MFI) and Weibull median fire intervals (WMFI) were calculated. The latter is considered a better estimator of central tendency for the typically nonnormal fire-interval distributions (Grissino-Mayer and Swetnam 1997; Grissino-Mayer et al. 2004).

For each unit, we also calculated the mean fire occurrence probability (MFOP) for two periods (stand origination to 1935 and to 2000). Defined by Guyette et al. (2006), MFOP is the number of years divided by the number of fires in a chronological period. Guyette et al. (2006) calculated the MFOP to account for the fire-free period prior to the first recorded fire. For each site, we defined the stand origination as the first year in which at least four samples were present that could potentially record a fire.

Results

Twenty-eight fires were recorded, of which 26 occurred from 1870 to 1933 (Table 1). Twelve fires scarred five or more samples and were classified as significant fires ($\geq 33.3\%$ of the samples were scarred); these fires occurred from 1877 to 1923. Most wounds attributed to fire were recorded on small-diameter trees; for all fires, the basal diameter of oaks at the time of wounding was 12.7 ± 0.7 cm (mean \pm SE). In most of the fires ($n = 24$), all wounds were located between annual growth rings, indicating occurrence in the dormant season (September to early April). In fire years, 147 of the 213 total wounds (69%) were on the uphill portion of the stem (300° clockwise to 60°), based on the uphill position recorded on the sample in the field. Of the 204 maple samples, only one exhibited a fire scar (a wound in a fire year); that maple, from Zaleski 2, had a wound in 1965.

Fire histories of the study units

REMA 2 had the greatest number of fires ($n = 7$) and significant fires ($n = 5$) (Table 1); fires were documented from 1877 to 1933. The 1917 significant fire had both dormant and earlywood scars, suggesting an early growing season fire. In the 1933 fire, most wounds were present in the late earlywood; in that fire, all seven scarred trees were young and small, having established in 1923 or 1924 and averaged only 5.1 cm in basal diameter (Table 1). We recorded six fires at REMA 3, three of which were significant, from 1878 to 1923 (Table 1; Fig. 1). As with REMA 2, the wounds in the 1917 fire indicate an early growing season fire; in the 1906 fire, all three wounds intersected the earlywood.

Zaleski 2 had evidence of six fires; five occurred from 1870 to 1928, and a sixth occurred in 1965 (Table 1). Although only the 1923 fire was classified as significant, it wounded 83% (15 of 18) of the samples; none of the other fires wounded more than three samples. No fires were recorded at Zaleski 2 during a 25 year period from stand origination (1844 to 1869). At Zaleski 3, the chronology was shorter, dating from 1880 to 2000. Although only three fires were recorded, both the 1917 and 1923 fires were significant. Again, the 1923 fire wounded a high percentage (61.9%)

Table 1. Summary data for the 28 fires documented on the six study units.

Study site, sample size, and chronology ^a	Fire year	Fire season ^b	Scarred trees (%)	No. of scarred trees	Total no. of trees	Diameter scarred (cm)	
						Mean	Range
REMA 2 <i>n</i> = 29 1855–2000	1877	D	50.0	6	12	8.6	7.0–10.7
	1885	D	66.7	8	12	13.0	9.5–17.2
	1895	D	25.0	3	12	14.4	13.5–15.2
	1900	D	50.0	6	12	18.1	15.4–23.1
	1917	D and E	50.0	6	12	22.0	18.0–28.8
	1923	D	50.0	9	18	13.1	3.3–25.8
	1933	E	20.7	7	29	5.1	2.7–7.5
REMA 3 <i>n</i> = 22 1858–2000	1878	D	23.1	3	13	7.4	4.6–10.5
	1885	D	38.5	5	13	11.0	6.7–14.5
	1895	D	57.1	8	14	14.2	5.5–19.5
	1906	E	23.5	3	17	18.4	12.1–21.5
	1917	D and E	33.3	7	21	11.7	3.9–21.7
	1923	D	18.2	4	22	16.8	8.6–25.0
Zaleski 2 <i>n</i> = 24 1844–2000	1870	D	75.0	3	4	4.7	4.2–5.4
	1879	D	33.3	3	9	5.0	1.2–8.3
	1917	D	16.7	3	18	13.3	6.3–18.1
	1923	D	83.3	15	18	16.0	7.5–29.8
	1928	D	12.5	3	24	11.1	4.0–15.6
	1965	D	12.5	3	24	22.5	16.8–33.7
Zaleski 3 <i>n</i> = 25 1880–2000	1914	D	22.2	4	18	5.2	3.8–6.8
	1917	D	35.0	7	20	8.6	4.9–13.6
	1923	D	61.9	13	21	10.3	6.3–17.2
Tar Hollow 2 <i>n</i> = 22 1844–2000	1883	D	71.4	5	7	7.9	5.7–13.7
	1900	D	26.7	4	15	4.4	1.5–8.0
	1926	D	22.7	5	22	13.4	8.0–24.0
Tar Hollow 3 <i>N</i> = 17 1899–2000	1900	D	50.0	2	4	6.4	3.0–6.8
	1912	D	25.0	3	12	7.2	3.7–10.7
	1984	D	17.6	3	17	40.7	36.3–47.0

Note: All data are from the oak samples. Years in bold type indicate fires that scarred five or more trees and $\geq 33.3\%$ of samples.

^aSample size is the total number of oak samples. Chronology period begins with the first year when four or more samples were present to record fires.

^bD, dormant season; E, earlywood; D and E, both dormant and earlywood wounds were present in the samples.

of the samples. All fire scars in both Zaleski units were in the dormant season.

We recorded three fires at Tar Hollow 2 from 1883 to 1926 (Table 1). No fires were documented in the 39 years from stand origin (1844) to the 1883 fire; that fire was the only significant fire, wounding five of seven trees. Tar Hollow 3 had the shortest chronology (1899–2000) of all units; fires were documented in 1900, 1912, and 1984. Only two trees were scarred in 1900, but this is included as a fire because of its concordance with the four trees scarred in 1900 in Tar Hollow 2. Only three trees were scarred in the 1912 and 1984 fires at Tar Hollow 3. As with Zaleski, all fire scars were located between annual growth rings, indicating dormant-season fires.

Fire-return intervals

In the period before active fire control and ending in 1935, composite mean fire intervals (MFI) only could be calculated at three of the six units (REMA 2, REMA 3, and

Zaleski 2). At these units, MFI ranged from 9.0 to 14.5 years (Table 2). Likewise, the composite Weibull median fire interval (WMFI) ranged from 9.1 years at REMA 2 to 11.3 years at Zaleski 2. For the same pre-1936 period, the mean fire occurrence probabilities (MFOP; Guyette et al. 2006), which also take into account the period of time prior to the first fire, ranged from 11.6 and 12.2 years at REMA 2 and REMA 3, respectively, to 30.7 years at Tar Hollow 2. For the five units originating in 1880 or before (all but Tar Hollow 3), there was a period of at least 20 years from stand origination to the first recorded fire. As only two fires were documented from 1936 to 2000, fire-interval calculations that end in 2000 are longer (Table 2). The WMFI ranged from 12.7 and 13.9 years at REMA 2 and REMA 3, respectively, to 35.4 years at Tar Hollow 2.

Fire and the establishment of oaks and maples

At REMA 2, all oak samples established prior to 1924, and nearly every maple recruited after the 1923 fire (Fig. 2a).

Fig. 1. Fire history diagram for REMA 3. The broken horizontal lines represent the growth years for the 22 oak samples. The solid triangles are wounds that were in a recorded fire year; vertical bars are wounds present in years not recorded as fire years. The six fire years are indicated by the vertical lines located above the timeline.

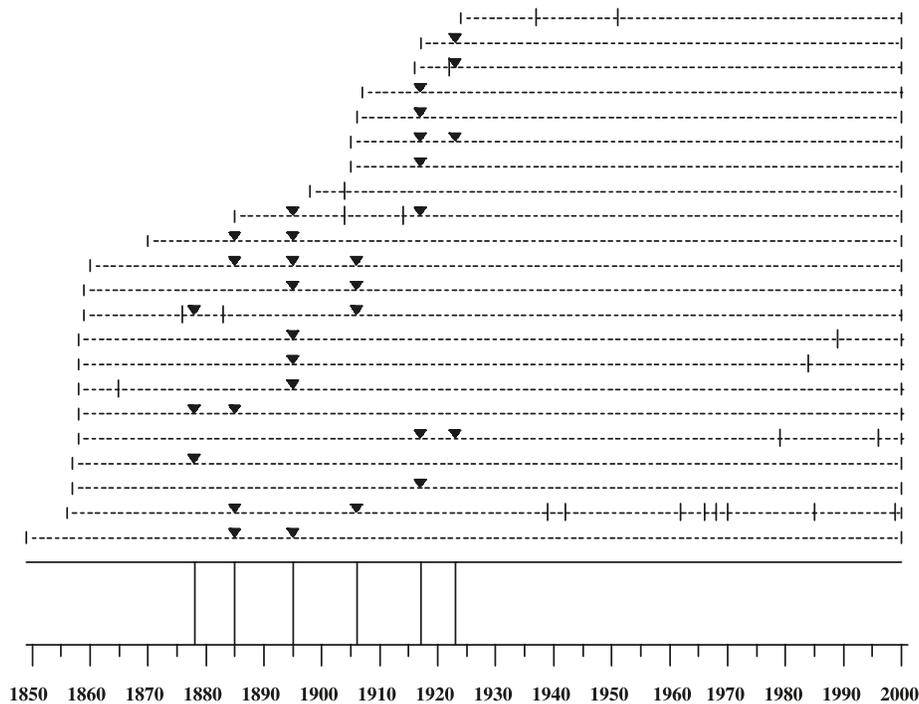


Table 2. Fire-return intervals (years) associated with the mean fire interval (MFI) and the Weibull median fire interval (WMFI) with 87.5% and 12.5% exceedence levels; also shown is the mean fire occurrence probability (MFOP), the number of years divided by the number of fires (sensu Guyette et al. 2006).

Study site	Period ending in 1935			Period ending in 2000		
	MFI	WMFI (87.5%–12.5%)	MFOP (years/fires)	MFI ^a	WMFI (87.5%–12.5%) ^a	MFOP (years/fires)
REMA 2	9.3	9.1 (4.8–14.1)	11.6 (81/7)	17.6	12.7 (2.8–36.1)	20.9 (146/7)
REMA 3	9.0	9.2 (6.7–11.3)	12.2 (73/6)	20.3	13.9 (2.6–42.4)	23.8 (143/6)
Zaleski 2	14.5	11.3 (2.8–28.8)	18.4 (92/5)	21.7	18.2 (5.5–40.3)	26.2 (157/6)
Zaleski 3	—	—	18.7 (56/3)	28.7	14.0 (1.5–63.2)	40.3 (121/3)
Tar Hollow 2	—	—	30.7 (92/3)	39.0	35.4 (13.3–68.2)	52.3 (157/3)
Tar Hollow 3	—	—	18.5 (37/2)	33.3	27.3 (7.6–64.2)	34.0 (102/3)

Note: A dash indicates that there were an insufficient number of fire events to calculate the interval.

^aFire interval calculations in these columns are based on a final incomplete interval ending in 2000.

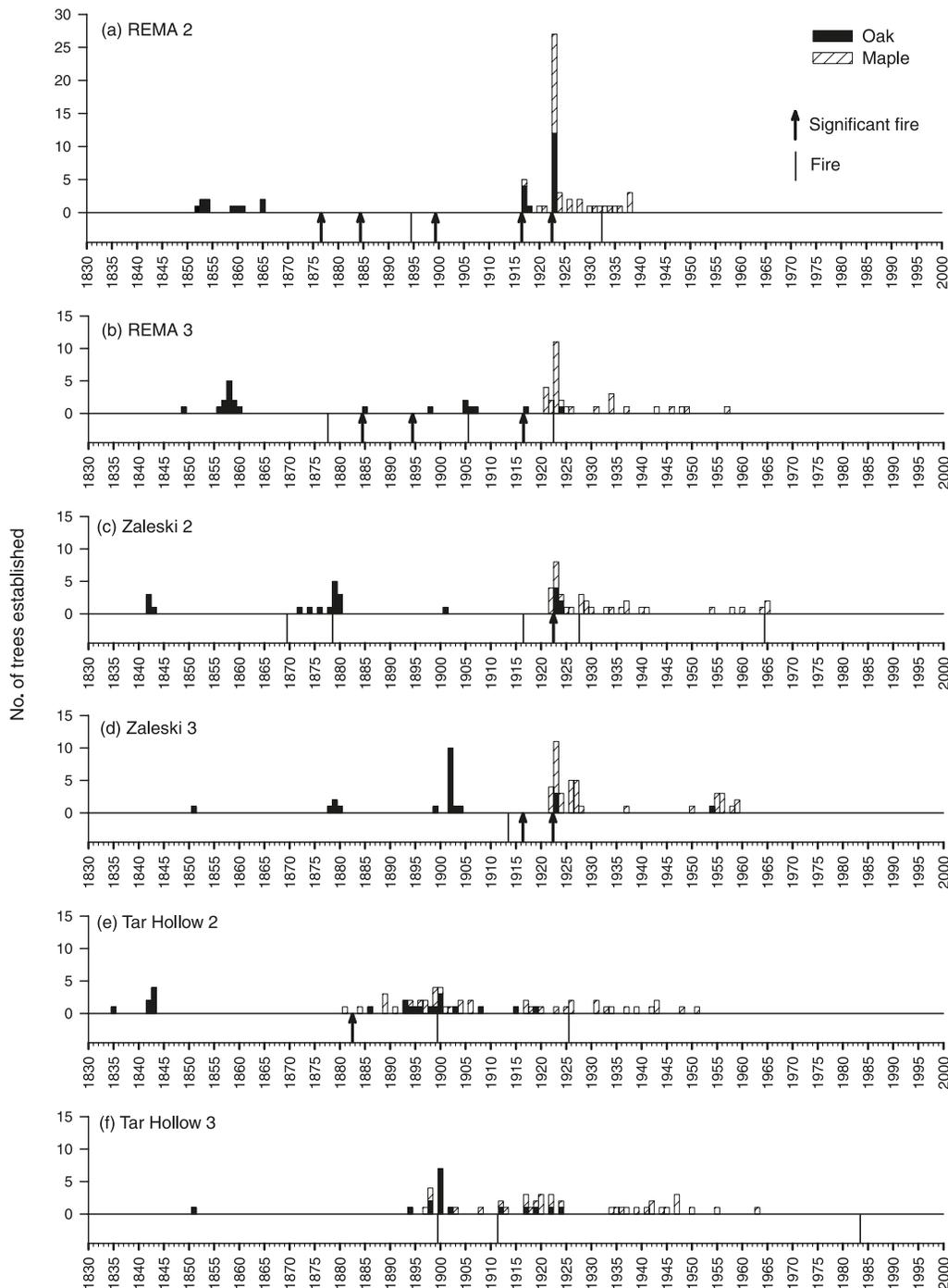
After an initial period of oak establishment (1852 to 1865), presumably after harvesting for the charcoal iron industry, there was a 51 year period (1866 to 1916) when no oak recruitment was recorded. Thereafter, two pulses of oak establishment were documented immediately after the significant fires of 1917 and 1923. No maples predated the 1917 fire, and several maples established between the 1917 and 1923 fires. In 1923, immediately after the last significant fire, 15 maples recruited. Thereafter, 17 maples established from 1924 to 1938.

At REMA 3, initial oak establishment occurred from 1849 to 1860. As with REMA 2, no establishment was recorded after 1924 (Fig. 2b). After 1860, there were no large pulses of oak establishment, but there were 7 years from 1885 to 1924 in which pith dates were recorded for one or two oaks. The oldest maple dated to 1921, and a pulse of 11 stems established in 1923, immediately after the last fire. An additional 12 maples established from 1924 to 1949.

The temporal patterns of fire and establishment at the Zaleski units were similar to those of REMA, remarkably so for the initiation of maple establishment and the corresponding cessation of oak recruitment. At Zaleski 2, four oaks established in the 1840s (Fig. 2c). There was a period of oak recruitment from 1872 to 1880, with a pulse of eight stems in 1879 and 1880, following the 1879 fire. After 1880, we record virtually no oak recruitment for 42 years (1881 to 1922). Oaks then established in 1923 and 1924, immediately after the 1923 fire which scarred 15 of 18 oaks. Maple establishment began in 1922 ($n = 4$), just before the 1923 fire; four others dated to 1923. Thereafter, 22 maples established from 1924 to 1965, with a maximum of three stems in a single year.

At Zaleski 3, we recorded 5 oaks that established before 1900 (primarily ca. 1880); then, 10 trees established in 1902 (Fig. 2d). The 1902 pulse of oak recruitment was not associ-

Fig. 2. (a–f) Temporal establishment of oaks and maples for the six study units. Fires are indicated by vertical lines above the timeline; significant fires, those with $\geq 33.3\%$ of samples wounded, are indicated by vertical arrows.



ated with a fire. As in unit 2, there was another period of oak establishment ($n = 5$) in 1923 and 1924, immediately following the 1923 significant fire; thereafter, we recorded only a single oak that established in 1954. As in unit 2, maple recruitment initiated in 1922 ($n = 4$), and eight trees established in 1923, directly after the significant fire. From 1926 to 1928, 11 maples established, and 11 others had pith dates from 1937 to 1959.

Tar Hollow 2 exhibited an early period of oak establish-

ment ($n = 8$) from 1835 to 1851, six of the eight trees had pith dates of 1842 and 1843 (Fig. 2e). We recorded no oak establishment from 1852 to 1885; 15 trees established from 1886 to 1919. There was a small pulse ($n = 3$) of oak recruitment in 1900 after the fire of that year. Unlike REMA and Zaleski, maple establishment began nearly 40 years earlier at Tar Hollow 2. Maples (both red and sugar) recruited for 70 years (1881 to 1951) in a fairly continuous manner but did not exhibit the large pulses recorded at REMA and Zaleski.

The oldest oak recorded in Tar Hollow 3 dated to 1851, but no other samples predated 1894 (Fig. 2f). We record fires in 1900 and 1912. The 1900 fire scarred two of the four samples, and there was a pulse of oak recruitment ($n = 6$) that year. Thereafter, six oaks had pith dates from 1902 to 1924; no more than one tree was recorded in any single year. Maple recruitment at Tar Hollow 3 spanned from 1897 to 1963. As in Tar Hollow 2, there were no large establishment events. At both Tar Hollow units, despite different patterns of fire and an earlier initiation of maple establishment compared with REMA and Zaleski, oak establishment ceased at the same time at all sites (ca. 1920 to 1925).

Spatial distribution of fire scars and tree establishment at REMA

Fires that occurred in 1885, 1895, 1917, and 1923 were recorded in units 2 and 3 (Fig. 3). The 1885 and 1917 fires were classified as significant in both units. By contrast, the presence of fire-scarred trees was limited to one unit in the other five fire years (1877, 1878, 1900, 1906 [not shown], and 1933). Presumably, these fires did not burn across the intermittent stream drainage separating the two units. Similarly, the stream drainage in the center of unit 2, running southwest, appears to have limited fire spread in several years when trees were scarred only northwest (1895 and 1900) or southeast (1933) of the drainage.

For all fire years, scarred oaks were located near oaks that were not scarred. The trees most prone to exhibiting fire scars were in the northern portion of unit 2, near the top of the ridge; two or more of the seven trees that had established there before the first fire in 1877 were scarred in all unit 2 fires prior to 1933.

Maple establishment is first shown in both units on the 1923 fire map (Fig. 3g); these trees established from 1917 to 1922 and survived the 1923 fire. In unit 3, most of the maples that established before 1923 were in areas where fire scars were not recorded on oaks in 1923, suggesting that those small trees were in unburned patches. In unit 2, all three maples predating 1923 are within 5–20 m of an oak with a 1923 fire scar; however, all three oaks with fire scars were small in 1923, each having established immediately after the 1917 fire. By the time of the 1933 fire (Fig. 3h), maples had established across most of the landscape. All of the maples in the 1933 fire map were relatively near scarred oaks and thus escaped that fire; none of these samples had 1933 wounds. However, the low-intensity and perhaps patchy nature of the 1933 spring growing season fire is suggested by the fact that only small oaks (mean basal diameter 5.1 cm) that established after the 1923 fire were scarred.

Radial growth and releases

The master chronologies show growth that is typical of trees from forest interior sites and show only several sustained release events (Fig. 4). Growth releases were identified at only two of the six units; however, none of these releases coincided with a fire. Zaleski 2 had a major release beginning in 1896, perhaps coinciding with a harvest based on its magnitude. No oak recruitment was associated with this release. A moderate release also was identified at this site for 1906. REMA 3 had a major release in 1864

(Fig. 4), although considerable variability in early growth associated with the small sample size may partially account for this release event. No growth releases were identified at Zaleski 3, REMA 2, or at the Tar Hollow units. At REMA 3, some oak recruitment preceded the 1864 release event, but there is no evidence that these were related (Figs. 2 and 4). These analyses, based on the standardized mean ring-width chronologies, indicate that fires were of insufficient intensity to cause standwide mortality and the release of surviving oaks.

Discussion

Historic fire regime

Generally, fires were frequent from ca. 1870 to 1935 as stands developed but were uncommon thereafter, reflecting the regional postsettlement history of anthropogenic fire and its suppression. A 1920–1922 forest survey of 10 southern Ohio counties reported that 25% of all forested land showed visible evidence of having burned at least once within the previous decade (ODNR, Ohio Division of Forestry, Columbus, Ohio). Data from the same survey indicated that 5% to 7% of forested land burned annually (Ohio Experiment Station 1922). Organized fire control was instituted in 1923, and its infrastructure and effectiveness developed rapidly. By 1935, 19 fire lookout towers had been erected in 8 southern Ohio counties, and 447 fire wardens were employed (Leete 1938). From 1926 to 1935, the mean annual forest acreage burned had been reduced to 0.8% (Leete 1938); from 1950 to 2000, it was further reduced to only 0.1% per year (ODNR, Division of Forestry, Columbus, Ohio).

Our study adds to the growing body of dendrochronological evidence that fire was frequent in the central hardwood region prior to organized fire control; examples include oak and oak–pine community types in the Missouri and Arkansas Ozarks (Cutter and Guyette 1994; Guyette et al. 2002; Guyette and Spetich 2003; Soucy et al. 2005); pine–oak communities in the southern Appalachians (Brose and Waldrop 2006); post oak (*Quercus stellata* Wang.) barrens in Indiana (Guyette et al. 2003) and Tennessee (Guyette and Stambaugh 2004); and oak forests in southern Ohio (Sutherland 1997; McEwan et al. 2007b), Maryland (Shumway et al. 2001), and West Virginia (Schuler and McClain 2003). The fire-return intervals that we calculated for the REMA and Zaleski sites, ranging from 9.1 years prior to 1936 to 18.2 years overall (WMFI), are within the range reported in those studies (2–24 years), despite our more conservative criteria for classifying fire years. However, the 35 year fire-return interval at Tar Hollow 2 exceeds the range in the other studies.

In the central hardwoods region, dissected topography is known to have limited the spread of fires historically (Guyette et al. 2002). In our study, mapped fire-scarred trees suggest that even relatively small intermittent stream drainages limited fire spread in some years, resulting in some fires that were recorded on, and presumably burned, only a portion of the 20 ha units. By contrast, several of the significant fires spanned two units, scarring trees as far as 900 m apart.

As other dendrochronological fire-history studies in the region have shown (e.g., Sutherland 1997; Shumway et al. 2001; McEwan et al. 2007b), the great majority of fires oc-

Fig. 3. (a–h) Spatial distribution of oaks and maples at REMA in eight fire years. Solid circles indicate oaks scarred by a fire in the year associated with the map, and open circles show oaks that were not scarred in that year. The shaded triangles indicate the location of maples that had established by the time of the 1923 (Fig. 3g) and 1933 (Fig. 3h) fire years. (No maples were documented to have established at the time of the 1917 fire or before.)

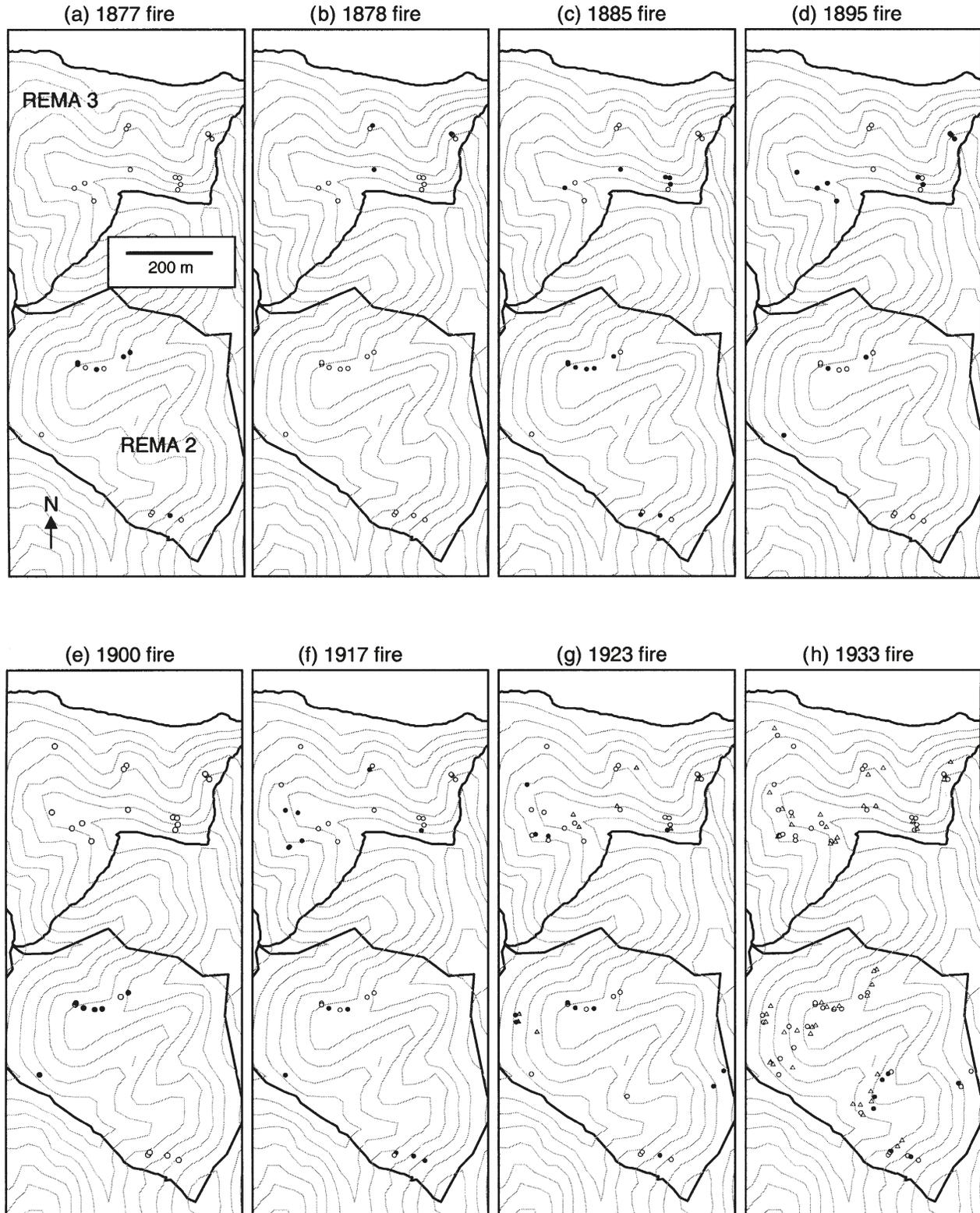
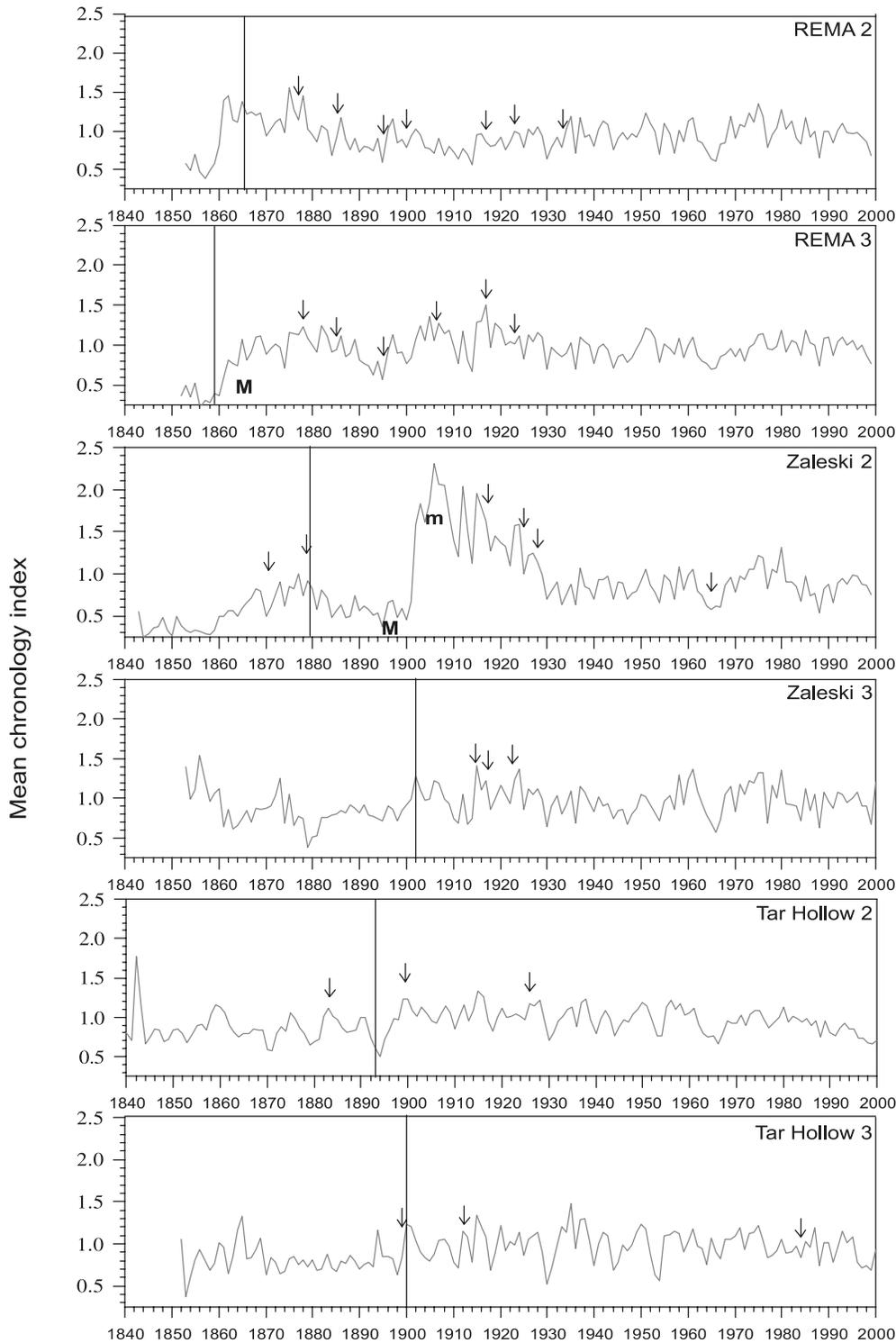


Fig. 4. Master tree ring chronologies (ARSTAN) showing fire events (vertical arrows) and the point when a minimum of 10 trees were averaged (vertical line) into the mean chronology. Major (**M**) and moderate releases (**m**) were only noted in the Zaleski 2 and REMA 3 chronologies.



curred in the dormant season (September to early April). Only fires in 1906, 1917, and 1933 at REMA had wounds located in the earlywood. In southern Ohio, radial growth (earlywood production) in oak begins in middle to late April, during bud-swelling and leaf unfolding (Phipps

1961). Oak cross sections collected in early May clearly show earlywood production, whereas samples from mid-June show latewood production (R.W. McEwan, Department of Forestry, University of Kentucky, Lexington, Ky., unpublished data). Thus, we estimate that fires exhibiting both

dormant and earlywood scars likely occurred in mid-April at the onset of radial growth (e.g., the 1917 REMA fire). The single fire (REMA 2 in 1933) that exhibited wounds intersecting the late portion of the earlywood probably occurred in May.

Sutherland (1997) and McEwan et al. (2007a) showed that historic fire occurrence in this region was not related strongly to monthly climatic conditions. Similarly, we recorded fires in both wet and dry periods. However, for the years in which fires occurred at more than one study site (1900, 1917, and 1923), all exhibited two or more months of drought conditions (Palmer drought severity index more negative than -1.5) the previous fall (1900, 1917, 1923) or also in the spring of the recorded fire year (1900).

The intensity of fires as these stands developed is difficult to determine with certainty because research is lacking that directly relates fire intensity to scarring in oak. However, several studies that have examined patterns of scarring in oak following prescribed fires provide some insight. Smith and Sutherland (1999) found that 14 of 18 small oak trees (4–23 cm DBH) had at least one fire scar after two low-intensity prescribed fires (flame lengths generally <50 cm with no overstory tree mortality). Guyette and Stambaugh (2004) showed that 35% to 65% of mostly small post oak trees (10–25 cm basal diameter) were scarred during three separate prescribed fires in an oak community in Tennessee. These fires burned 72%–93% of the area and reduced stand density (mostly small-diameter trees) by 35%. However, in both studies, only trees with visible bark char were selected for sampling. In our study, we found that, on average, 40% of the oak samples, most of which were small at the time (5 to 25 cm basal diameter) were scarred in the historic fires. These scarring percentages suggest that the fires would have been similar in intensity to the prescribed fires reported by Smith and Sutherland (1999) and Guyette and Stambaugh (2004). Although pulses of oak establishment immediately after some historic fires in our study suggest abundant resprouting after top kill, there is no evidence of high-severity, stand-replacement fires even in these relatively young, regenerating stands.

McEwan et al. (2007a) reported that during 15 separate prescribed fires that were similar in intensity to those in Smith and Sutherland (1999), the scarring rate was much lower (12.6%) in white oak. However, because the sample trees in that study were much larger (most were >20 cm DBH), it is difficult to compare those scarring percentages with the historic scarring of small trees in our study.

Five years after a prescribed fire, Wendel and Smith (1986) found that 66% of overstory trees (all species, >12.7 cm DBH) exhibited fire scars visible on the exterior of the stem as exposed wood with callous tissue. The fire in their study was higher in intensity, reducing stand basal area by nearly 20%. The high scarring percentage of larger trees in their study suggests a higher intensity fire than was typical of the historic fires in our study.

Fire, land use, and tree establishment

At REMA and Zaleski, periods of oak and maple establishment were related to specific fire events as these stands developed. The establishment and subsequent survival of maples generally began immediately after the cessation of

significant fires, i.e., fires that wounded at least one-third of the oak samples. The final oak establishment event also occurred directly after the last significant fire at three of the four REMA and Zaleski units. Because maples seldom were recorded as witness trees in upland forests just before Euro-American settlement (Beatley 1959; Dyer 2001), these results lend support to the hypothesis that organized fire control facilitated the invasion of maples into the uplands from the more fire-protected lowlands (Abrams 1998).

The temporal patterns of fire history and maple establishment were similar at all four units at REMA and Zaleski. All units had periodic fires from ca. 1870 to 1925, and all units burned in both 1917 and 1923; in each of those years, fires were significant in three units. The initiation of maple establishment was similar in that none was documented in any units before the 1917 fires. Limited establishment was documented between the 1917 and 1923 fires, and large pulses occurred immediately after the 1923 fires followed by continuous establishment into the 1960s. The large pulses of maple establishment after the 1923 fires suggest resprouting from previously established individuals. Red maple, which accounted for 89% of the maple samples at REMA and Zaleski, has thin bark and is highly susceptible to top kill by fire (Harmon 1984; Regelbrugge and Smith 1994; Hutchinson et al. 2005); however, it also sprouts prolifically after topkill (Albrecht and McCarthy 2006; Blankenship and Arthur 2006). Maples probably began recruiting into these stands earlier than we document, perhaps much earlier, but presumably were being killed or top-killed until the cessation of fires.

The limited establishment and survival of maples before the 1923 fires (1917 to 1922) in all units may have resulted from several factors. Firstly, wildfires usually burn in a mosaic pattern, particularly in dissected landscapes, resulting in variable fire intensities and including unburned patches. Established maples may have escaped the 1923 fires in unburned patches. We also speculate that the initiation of maple establishment at REMA and Zaleski may have been facilitated by reduced anthropogenic land use, particularly by livestock in open-range woodland livestock grazing (Green 1907). The human population of Vinton County declined steadily with the demise of the iron furnace industry from a maximum of 17 223 in 1880 to 10 287 by 1930 (Vinton County Ohio Genealogy 2005). During the same period, farmland in the county decreased from 93 283 to 61 559 ha, and most of these lands reverted to forest (Bromley 1934a). Woodland grazing also likely decreased during this period, which would have favored the recruitment of trees, including maples. Brose and Waldrop (2006) showed that the cessation of livestock grazing in the Great Smoky Mountains National Park contributed to increased tree recruitment there in the 1920s and 1930s.

Oak also exhibited pulses of establishment immediately after some fires, suggesting resprouting from previously established stems. However, some fires were not followed by pulses of oak establishment. The final period of oak establishment occurred immediately after the 1923 fires; thereafter, we recorded virtually no additional oak stems. These data suggest that the large increase in maple establishment after the cessation of fires contributed via competition to the lack of subsequent oak recruitment. The absence of fire

after 1923, probably coupled with reduced woodland grazing, also likely facilitated the development of higher stand densities. The resulting closed-canopy conditions that developed would have greatly limited the ability of the relatively shade-intolerant oaks to establish from seed (Beck 1970) but not the shade-tolerant red maple, which can persist for long periods beneath a canopy (Tift and Fajvan 1999). Thus, further oak recruitment from seed, followed by growth and survival, probably was limited by a combination of shading and competition from both overstory trees and understory maples after fires ceased (e.g., Aldrich et al. 2005).

The history of fire and tree establishment at Tar Hollow differed from that of REMA and Zaleski in several aspects. First, at Tar Hollow, there were fewer historical fires ($n = 5$) and only one was significant. In all, we recorded only 19 historic fire scars at Tar Hollow compared with 48 at Zaleski and 75 at REMA.

The temporal pattern of maple establishment also differed, beginning nearly 40 years earlier (1881) and not exhibiting the distinct pulses after fire cessation that occurred at REMA and Zaleski. Tar Hollow also differed in that there was a long period of fairly continuous oak establishment (ca. 1890 to 1925), that coincided with the continuous recruitment of maples. These differences in fire and regeneration among sites may have resulted from different human land use.

Timber harvesting in the 1800s at Tar Hollow was not associated with charcoal production as at REMA and Zaleski and, thus, may have differed in intensity and extent. Perhaps more important is the evidence of greater and more varied human land use at the Tar Hollow site. In the 1930s, several Land Utilization Project (LUP) areas were established in which the State of Ohio purchased submarginal farmlands and then resettled the occupants (Bromley 1934a, 1934b). The REMA and Zaleski study sites were located near LUP areas while the Tar Hollow site was within the Ross-Hocking LUP. Land titles and appraisals that included detailed ownership and land-use maps from the time of purchase (ca. 1935) indicate that the Tar Hollow site consisted of a number of small parcels of mixed-ownership (ODNR, Division of Forestry, Regional Office, Chillicothe, Ohio). The maps indicate a patchy mixture of cover types: the most abundant was “forest land (including woodland pasture),” but it also included some areas of “grazing land (grazing or open pasture)” and a smaller portion as “crop land (including orchard and hay meadows).” The more varied land uses at Tar Hollow likely would have created a more patchy distribution of disturbances (fire, grazing, and harvesting). In particular, the patchy ownership and land use might have limited fire spread, resulting in the lower observed occurrence of fire. In turn, fewer fires probably facilitated the recruitment and survival of maples beginning much earlier at this site. At Tar Hollow, woodland grazing may have been more prevalent for a longer period with direct human occupation into the mid-1930s, potentially limiting the large pulses of maple establishment that occurred at REMA and Zaleski. Although fires generally were less frequent and wounded fewer trees at Tar Hollow, these units also developed into oak-dominated forests.

Other potential factors affecting tree establishment

In addition to fire and human land use (particularly wood-

land grazing), the regeneration of oak forests was surely influenced by dramatic changes in wildlife populations. The decline and extirpation of the acorn-consuming white-tailed deer (*Odocoileus virginianus* (Zimmermann)), wild turkeys (*Meleagris gallopavo* L.), and passenger pigeons (*Ectopistes migratorius* (L.)) occurred from the mid-1800s to the early 1900s, as these stands were developing (Chapman 1938). Although these declines could have benefited oak regeneration from seed, the consumption of acorns and grazing of seedlings by domestic livestock probably were widespread during this period.

No deer were present in Ohio from 1904 to 1922 when a restocking program was initiated (Chapman 1938). By 1938, it was estimated that only 2000 deer were in Ohio (Chapman 1938); the current estimate is 650 000 (ODNR, Division of Wildlife, Columbus, Ohio). Thus, excessive deer browsing clearly would not have contributed to the cessation of oak recruitment ca. 1925. In fact, a lack of deer browsing, the cessation of fire, and a decrease in livestock grazing may have facilitated the dramatic increase in maple establishment during the 1920s and 1930s.

It also is unlikely that American chestnut (*Castanea dentata* (Marsh.) Borkh.) mortality, caused by the chestnut blight fungus, facilitated the initial recruitment of maple in these stands. Even at REMA and Zaleski where maple recruitment began later (ca. 1920), it predated the arrival of chestnut blight, which caused mortality in Vinton County primarily from 1928 to 1936 (Beatley 1959). Also, chestnut accounted for only 4%–6% of witness trees ca. 1800 (Beatley 1959).

Selective harvesting was common after the mid-1930s on the Zaleski and Tar Hollow State Forests and at the REMA, then owned by D.B. Frampton and Co. (Beatley 1959). Previous work on sites near our REMA sites showed some growth releases suggestive of selective harvesting (Hutchinson et al. 2003). However, our data indicate that, in the absence of periodic fire, canopy disturbances after ca. 1925 did not facilitate oak recruitment. Similarly, during the fire control era, small openings in closed-canopy stands would have favored the growth of maples, which can respond with rapid growth even after long periods of suppression (Tift and Fajvan 1999).

Implications for oak regeneration today

Our results show the past importance of periodic fire in sustaining oak establishment and in limiting maple recruitment as stands developed. However, in many oak forests, there is now an abundance of maples in the midstory that are large enough to be fire resistant. Also, many forests that remain dominated by overstory oaks may be too dense to support oak regeneration even if the maple midstory could be removed with fire. Research has shown that simply returning low-intensity prescribed fires to fully stocked stands does not open the canopy sufficiently to improve the competitive status of oak regeneration (Hutchinson et al. 2005; Blankenship and Arthur 2006). Similar to the past importance of fire in early stand development, oak regeneration has improved when prescribed fire was applied to open-structured stands that developed after partial harvest (Kruger and Reich 1997; Brose and Van Lear 1998; Iverson et al. 2008). However, other studies have shown that the timing

and intensity of the mechanical treatments and fire are critical to their success (Franklin et al. 2003; Albrecht and McCarthy 2006). Although fire was important in sustaining oak forests in the past, the legacy of prolonged fire exclusion necessitates research to refine oak regeneration prescriptions that incorporate canopy disturbances, fire, and other tools (Brose et al. 2006).

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