HISTORY OF FIRE IN EASTERN OAK FORESTS AND IMPLICATIONS FOR RESTORATION

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Abstract.—Our understanding of long-term fire history in the eastern United States is derived from the interpretation of a variety of archives. While cultural records are available for some sites, biological archives are most frequently used to reconstruct long-term historical fire regimes. The three most commonly used biological archives in eastern oak forests include: the relative abundance of micro- and macroscopic charcoal found in lake and wetland sediment cores, charcoal macrofossils recovered from mineral soil, and dated fire scars on tree cross-sections. Quantitative data from these biological records are essential to fully elucidate the relationships between fire and oak forest dynamics. In addition to providing a basis for the development and refinement of ecological theory, these data have practical utility as they can be used in restoration planning to set desired future conditions and establish silvicultural treatments that maintain oak dominance or mimic historical disturbance regimes. Here we review the three biological archives most commonly used to reconstruct historical fire regimes in the Central Hardwood Forest Region, synthesize results of investigations that have relied upon these techniques, and discuss the implications of these findings for restoration efforts. At present, ca. 100 fire reconstructions have been developed from fire scarred trees and soil and sedimentary charcoal in the region. Results from the reviewed published studies reveal that fire histories are site specific. Therefore, managers focused on ecological restoration are best advised to construct a place-based history rather than rely solely on results from other studies to set restoration targets and monitor treatment success.

INTRODUCTION

Over the past several decades the role of fire in oak (*Quercus*) forests throughout the eastern United States has received increased attention driven largely by successional changes hypothesized to be caused by 20th century human alteration of fire regimes (Abrams and Downs 1990, Cho and Boerner 1991, Goebel and Hix 1997, Lorimer 1993). In addition, concern that fuel loadings have exceeded the historic range of variability has generated interest in the history of fire in oak forests (Brose and others 2001, Graham and McCarthy 2006, Loucks and others 2008).

Vast areas of the eastern United States landscape are characterized by oak forest cover (Braun 1950, Dyer 2006). Paleoecological investigations indicate that oak has dominated forest communities of the region throughout much of the Holocene. However, a widespread pattern of forest composition change is evident throughout eastern oak forests. Oak regeneration failure has been reported from oak-dominated stands over a variety of site types. Coupled with this regeneration failure is an increase in the density and dominance of mesic species, particularly sugar maple (*Acer saccharum* Marsh.) and red maple (*Acer rubrum* L.) (Abrams 1998, Fei and Steiner 2009, Lorimer 1984).

The profusion of quantitative data reported from sites throughout the eastern United States has led many researchers to project a pervasive and inevitable transition from oak systems to those dominated by maple and other mesic taxa (Abrams and Nowacki 2008, Nowacki and Abrams 2008). This change in species dominance will undoubtedly have major ramifications for biodiversity, wildlife population densities, timber production, and a host of ecosystem processes such as forest hydrology, nutrient cycling, and fuel loading (Alexander and Arthur 2010, McShea and others 2007, Nowacki and Abrams 2008). Active fire suppression that began in the early 20th century is the most often cited explanation for the oak replacement pattern. While variability exists at the species level, oaks are considered tolerant of fire and only moderately tolerant of shade. Adaptations to fire include thick bark, the ability to stump sprout, and resistance to rot after scarring (Abrams 1992, Smith and Sutherland 1999). In contrast, maple and other mesic taxa have morphological characteristics such as thin bark and shallow rooting that make them fire-sensitive. Therefore, it is hypothesized that historic surface fires maintained oak dominance by removing more mesophytic, shade-tolerant, and fire-sensitive competition from the understory (Abrams 1992, Lorimer 2001, Nowacki and Abrams 2008). While alternative hypotheses have been proposed to explain this successional shift (e.g., climate change, alterations in land use, facilitative processes, extirpation of American chestnut (*Castanea dentata* [Marsh.] Borkh.), and changes in wildlife population densities (Hart and others 2008b, Lorimer 1993, McEwan and others 2011), the oak-fire hypothesis is undoubtedly the dominant paradigm. As such, quantification of historical fire regimes of oak ecosystems is essential.

Our understanding of the history of fire in eastern oak systems is derived from the interpretation of a variety of archives. To reconstruct fire history, researchers have relied upon witness tree analyses, field notes from land surveyors, early explorer and European settler accounts, and other land-use records (Ruffner 2006, Russell 1983, Whitney 1994). While documentary or cultural archives such as these are available for some sites, reconstructions of long-term historical fire regimes are typically developed using biological archives. Biological records used to document past fire events include dendrochronology or fire scar analysis; charcoal analysis of lake sediments, wetlands, or peat bogs; black carbon analysis of marine sediments; pedanthracology or macroscopic charcoal analysis in mineral soil; molecular markers of combustion; fuel and soil magnetism; and sedimentology (Conedera and others 2009). The three most commonly used biological archives of fire history in eastern oak forests include: the relative abundance or influx of micro- and macroscopic charcoal found in lake and wetland sediment cores, charcoal macrofossils recovered from mineral soil, and dated fire scars on tree cross-sections. Quantitative data from these biological records are essential to fully elucidate the relationships between fire and oak forest dynamics. In addition to providing a basis for the development and refinement of ecological theory, these data have practical utility as they can be used in restoration planning to set desired future conditions and establish silvicultural treatments that maintain oak dominance or mimic historical disturbance regimes.

The goal of this paper is to review the three biological archives most commonly used to reconstruct historical fire regimes, synthesize results of investigations that have relied upon these techniques, and discuss the implications of these findings for restoration efforts. We limited our review to the Central Hardwood Forest Region (CHFR) because a formal eastern oak forest unit is not recognized, the CHFR is a well established spatial unit, and oak is the dominant genus of the region. Several CHFR boundaries are accepted and we chose those defined by Fralish and Franklin (2002) and Fralish (2003).

BACKGROUND ON BIOLOGICAL FIRE RECONSTRUCTION TECHNIQUES

Sedimentary Charcoal Analysis

Charcoal is produced during fire events as organic material is partially combusted. This combustion results in black pyrogenic carbon ranging from soot and graphite particles to coarse charcoal fragments and charred wood (Conedera and others 2009, Ohlson and others 2009). Microscopic (ca. 10-200 µm length) and macroscopic (ca. >100-200 µm length) charcoal in sediment cores retrieved from lakes, wetlands, and peat bogs may be used to reconstruct historical fire characteristics (e.g., Delcourt and Delcourt 1997, 1998; Delcourt and others 1998). In these paleoecological analyses, the relative abundance or influx of charcoal is used to assess fire frequency and/or magnitude. The primary advantage of this biological archive is the depth of record, as it is possible to document variability in vegetation composition and fire spanning the Holocene (Clark and others 1996, Delcourt and others 1998). These records reveal periods, rather than dates, when fire was more or less common based on the relative position and abundance of the quantified charcoal in the varved (i.e., layered) sediment core. Consequently, temporal resolution is coarse relative to macroscopic soil charcoal or fire scar analyses. In fact, the temporal resolution of this biological archive exceeds the hypothesized return interval of fire in many oak forests. In addition, sedimentary charcoal records are not spatially explicit as lakes receive charcoal inputs from broad source areas (Clark 1988, Clark and Royall 1996). Calibration studies have demonstrated that macroscopic charcoal particles typically originate within a few hundred meters of deposition sites while microcharcoal may originate up to 100 km from the deposition site (Clark 1989, 1990; Clark and others 1998; Patterson and others 1987). Thus, documented microcharcoal could in fact have originated in a non-oak dominated stand kilometers from the study site and even macrocharcoal could originate from fire in xeric, pine (*Pinus*)-dominated stands that may not be representative of local forest composition. Furthermore, fires in oak forests are typically low intensity burns, and the quantity of charcoal produced from such events may be negligible and undetectable in the sedimentary record (Abrams and Seischab 1997). Therefore, sediment cores from lakes and wetlands may not provide accurate records of fire frequency and be biased towards the documentation of intense and/or high magnitude events. Nonetheless, these records are useful to understand long-term patterns of oak forest composition and the relative importance of fire in these systems.

Soil Charcoal Analysis

Macroscopic (generally considered >2 mm length) charcoal fragments recovered from soil cores provide historical fire data at fine spatial resolutions. Macroscopic charcoal particles are sufficiently large to resist entrainment by wind during or after fires and by overland flow on hillslopes. These macrofossils are considered primary charcoal and provide evidence of historical fire at the stand-scale (Gavin and others 2003, Hart and others 2008a, Talon and others 2005) though even larger pieces of charcoal are likely formed in situ and indicate fire at the exact location of the soil core sample (Gavin and others 2003, Ohlson and Tryterud 2000). In addition to fine spatial resolution, macroscopic soil charcoal provides long-term fire records. Mean residence time of macroscopic charcoal varies by geographic location, but charcoal may be preserved in mineral soils of the eastern United States for up to ca. 10,000 years (Fesenmyer and Christensen 2010, Hart and others 2008a). Therefore, charcoal macrofossils may provide fire history records at the stand-scale throughout the Holocene. While the utility has not been fully explored in eastern oak systems, charcoal macrofossils can be identified to species or genera providing information on taxa that inhabited stands that were disturbed by fire. The major limitations to this biological archive include the inbuilt age error (Gavin 2001) associated with accelerator mass spectrometry (AMS) ^{14}C dating of the charcoal macrofossils. This technique actually provides the date that carbon was assimilated by the plant rather than the time of the fire event. This dating analysis is also cost prohibitive, and many samples are required to develop robust fire histories. Macroscopic soil charcoal analysis may indeed be the best method to reconstruct long-term fire histories in mesic oak stands. However, more methodological studies in the eastern United States are warranted (e.g., inbuilt age error estimates by species and site type, charcoal loss during subsequent fire, and charcoal transport by size and site condition).

Fire Scar Analysis

Forest fire histories are often reconstructed by assigning the calendar year and often the season of formation to fire scars found on tree cross-sections (Fritts and Swetnam 1989, Kipfmueller and Swetnam 2001). Fire scar analysis provides the finest spatial and temporal resolution of the three biological archives most commonly used. As trees are sessile, the spatial resolution is known to the exact location of the sampled individual (Kipfmueller and Swetnam 2001, Swetnam and others 1999). This allows for reconstruction of the spatial extent of past fires. Along with forest composition and age structure data, the magnitude of the historical disturbances can also be documented which provides information on the role of fire in forest community organization. Annual resolution allows researchers to analyze historic fires with regard to short-term forcing factors that may influence fire characteristics (e.g., contemporaneous and previous climate characteristics, land-use change). Furthermore, intra-annual resolution allows for the documentation of fire seasonality, shifts in which may provide information on ignition sources (Lafon 2010). Though fire scar analysis provides annual or intra-annual resolution of fire data at fine spatial resolution, this line of evidence is inherently limited by the occurrence of old trees. Thus, the temporal depth of record is constrained by the age of the trees or remnant wood on the site. In the eastern United States, this archive provides records typically extending to a maximum of 400 years and often much less. Fire scar analyses are further constrained by tree selection and sample extraction. Long fire-free periods allow for wounds from prior fires to heal, and damaged trees may, therefore, not reveal external diagnostic characteristics of the records contained within. In addition, tree morphology (e.g., thick bark) may prevent scarring from low intensity surface fires (Guyette and others 2006a, McEwan and others 2007a, Smith and Sutherland 1999), resulting in an underrepresentation of these fires in the reconstructed dataset. Similarly, stand-replacing fires are also likely to be underrepresented in historical fire datasets as these events remove wood thereby destroying direct dendroecological evidence of the disturbance (Guyette and others 2006a). Fire scar analysis typically requires that complete cross-sections or partial wedges are removed from trees (Arno and Sneck 1977, Baisan and Swetnam 1990). While logs and standing dead trees can be sampled, attaining an appropriate sample depth may require the partial destruction of living trees. Even if only partial wedges are collected, this sampling scheme is restricted on many sites because it affects the structural integrity of stems and causes the trees to be more susceptible to pathogens.

GENERAL TRENDS

Sedimentary Charcoal Analysis

In the CHFR, fewer than 10 published studies have used charcoal analyzed from sediment cores to discern information on the long-term patterns of vegetation and fire (Table 1); however, several important sedimentary charcoal studies (e.g., Clark and others 1996, Clark and Royall 1996) have been conducted just outside the bounds of the CHFR. Collectively, studies from within the CHFR have

Table 1.—Descriptive data for all sedimentary charcoal sites from published studies in the Central Hardwood Forest Region

Reference	State	Length of record
Delcourt and others 1998	KY	9,500 YBP
Delcourt and Delcourt 1997	NC	3,900 YBP
Cridlebaugh 1984	TN	900 YBP
Cridlebaugh 1984	TN	2,800 YBP
Haas 2008	TN	425 YBP
Haas 2008	TN	2,800 YBP
Kneller and Peteet 1999	VA	17,345 YBP
Kneller and Peteet 1993	VA	17,130 YBP
White 2007	WV	8,180 YBP

reported nine sedimentary charcoal records from six different sites (multiple studies were conducted at the same site). The sedimentary charcoal studies for the CHFR are clustered in the central and southern Appalachian Highlands (Fig. 1). The longest record from this archive extends over 17,000 years before present (YBP) and shows an increase in charcoal abundance coincident with the rise of the oak-hickory (*Carya*) forest type in the central Appalachians at the beginning of the Holocene (Kneller and Peteet 1999). This marks the beginning of the Holocene and rapid climate change and does not provide that increased fire frequency was a causal factor.

No clear ubiquitous patterns were evident as the results from the studies revealed unique fire histories based on the abundance of charcoal in the sedimentary record. The results emphasize that fire history is region, landscape, and even site specific. Nonetheless, useful information on the relationships between humans, fire, and vegetation was gleaned from these studies. In all these paleoecological investigations, charcoal recovered from sediment cores exceeded the amounts the authors hypothesized would be produced by natural ignitions, leading them to speculate that most of the fires were from human ignitions. Working from this assumption, human use of fire generally

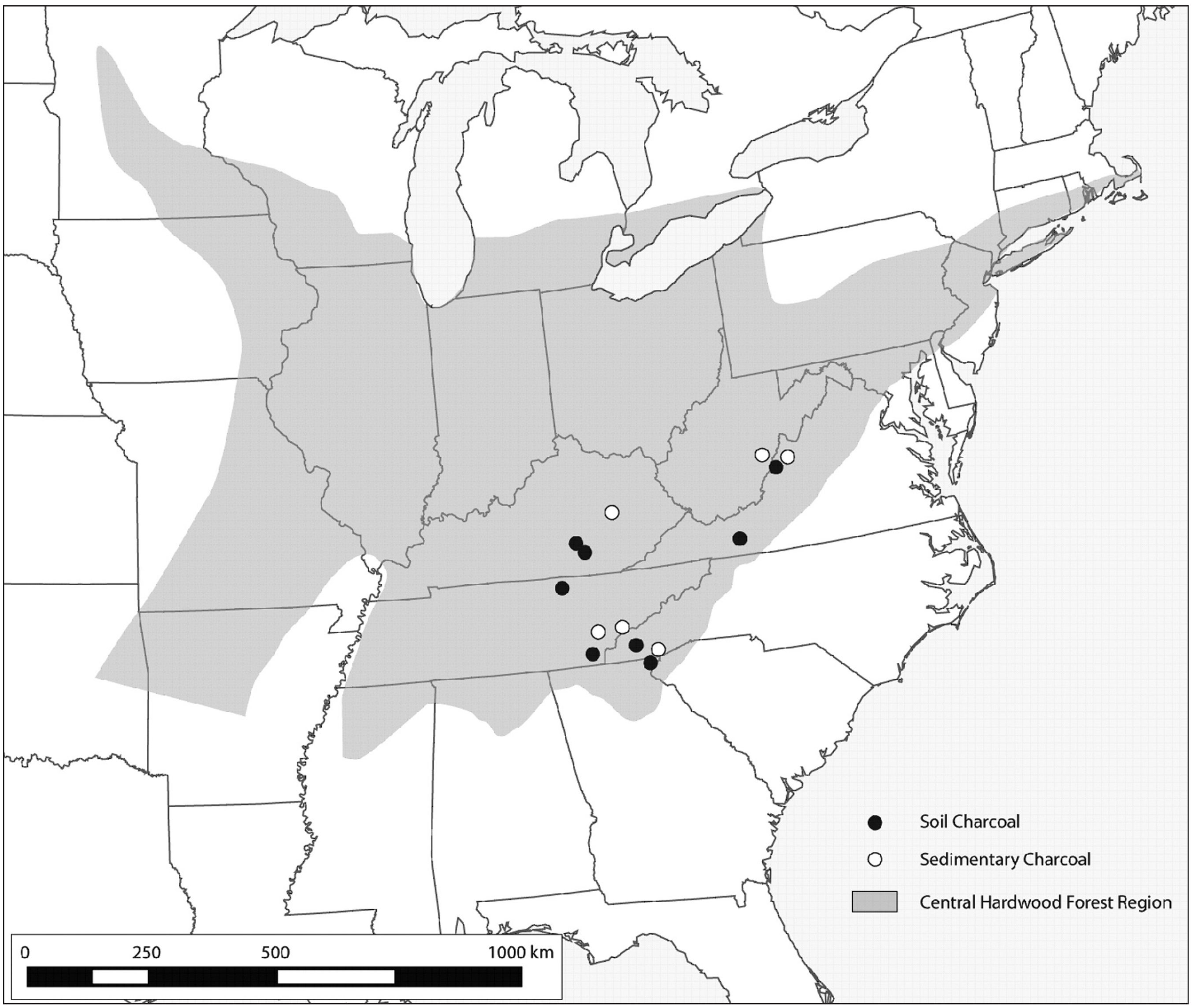

Figure 1.—Map of the Central Hardwood Forest Region (Fralish 2003, Fralish and Franklin 2002) and the location of sites with fire reconstructions based on analysis of soil and sedimentary charcoal.

increased during the Woodland cultural period (ca. 3,000 YBP) (Delcourt and Delcourt 1998). The abundance of charcoal from a site in the Ridge and Valley of east Tennessee peaked at the transition from Woodland to Mississippian periods (ca. 1,000 YBP) and from Mississippian to historic periods (ca. 300 YBP) (Delcourt and Delcourt 1998). Delcourt and Delcourt (1997) hypothesized that fires, at least of the southern Appalachian Highlands, were largely restricted to ridgetops and upper slopes and that lower slope positions supporting more mesic species were relatively protected from Native-set fires prior to European settlement. Additionally, they speculated that human-set fires in the southern Appalachians represented intermediate-scale disturbances that emphasized ecotones, increased gamma diversity, and increased the abundance of oak species on upper slope positions. Aboriginal fires would have likely facilitated and maintained oak dominance (and that of other disturbance dependent taxa as well) on ridgetops and upper slopes. Even at a local scale, these anthropogenic disturbances may have resulted in a patchwork of forest types that included fire-adapted and fire-tolerant species at various stages of succession (Delcourt and Delcourt 1997, Delcourt and others 1998).

Soil Charcoal Analysis

To date, macroscopic charcoal recovered from soil samples has been used in three published studies to reconstruct fire history in the CHFR (Table 2). These three studies presented data from nine different sites located in the southern Appalachian Highlands (Fig. 1). However, only Hart and others (2008a) work exclusively in oak dominated stands. Dated fire events (from AMS ^{14}C analyses) were only reported in two of these studies (Fesenmyer and Christensen 2010, Hart and others 2008a). Collectively, these two studies reported 87 AMS dates from charcoal macrofossils recovered from soil samples; however, only Fesenmyer and Christensen (2010) had sufficient dating to provide meaningful information on changes in fire frequency for their study site. Nonetheless, each of these studies made contributions to our understanding of historic fire regimes and the use of this method in the CHFR.

Welch (1999) established that macroscopic charcoal could be recovered from mineral soil in the temperate region of North America, that charcoal was abundant in pine and mixed pine-oak dominated stands of the southern Appalachians, and that charcoal accumulation did not vary by slope position indicating its presence is evidence of local fire. Hart and others (2008a) were the first to use macroscopic soil charcoal in mineral soils to elucidate fire history information in oak stands. Their study established that charcoal could be used to reconstruct stand-scale fire history in mesic oak systems, that charcoal macrofossils can be preserved in mineral soils of the region for millennia, and that macroscopic charcoal fragments could be identified to document taxa of the region that previously

Table 2.—Descriptive data for all soil macrocharcoal sites from published studies in the Central Hardwood Forest Region

Reference	State	Length of record	Number of radiocarbon dates
Welch 1999	GA	na	0
Welch 1999	KY	na	0
Welch 1999	KY	na	0
Welch 1999	NC	na	0
Fesenmyer and Christensen 2010	NC	10,570 YBP[a]	82
Welch 1999	TN	na	0
Hart and others 2008a	TN	6,735 YBP	5
Welch 1999	VA	na	0
Welch 1999	VA	na	0

[a]Only a single date was older than 4,000 YBP.

inhabited sites that burned during previous fires. To date, Fesenmyer and Christensen (2010) published the most extensive macroscopic soil charcoal study in the CHFR. They provided that even protected microsites devoid of trees (e.g., near rock outcrops) still had sufficient mixing of soil to require AMS dating of charcoal (i.e., depth does not correspond to charcoal age), that differences in fire frequency could be detected with this archive between mesic and xeric sites, and that fire frequency increased ca. 4,000 YBP (during the late Archaic period) and increased drastically ca. 1,000 YBP for their study site in the Blue Ridge physiographic province. In fact, only one charcoal date was older than 4,000 YBP. This drastic increase in fire frequency at 1,000 YBP was attributed to the rise of the Mississippian cultural tradition.

Fire Scar Analysis

We reviewed fire scar-based data from more than 70 sites in the CHFR representing 35 different published studies (Fig 2, Table 3). Of all biologically derived fire histories in the region, over 80 percent have been developed using fire scarred trees. The longest tree ring based fire records begin in 1581 (located in

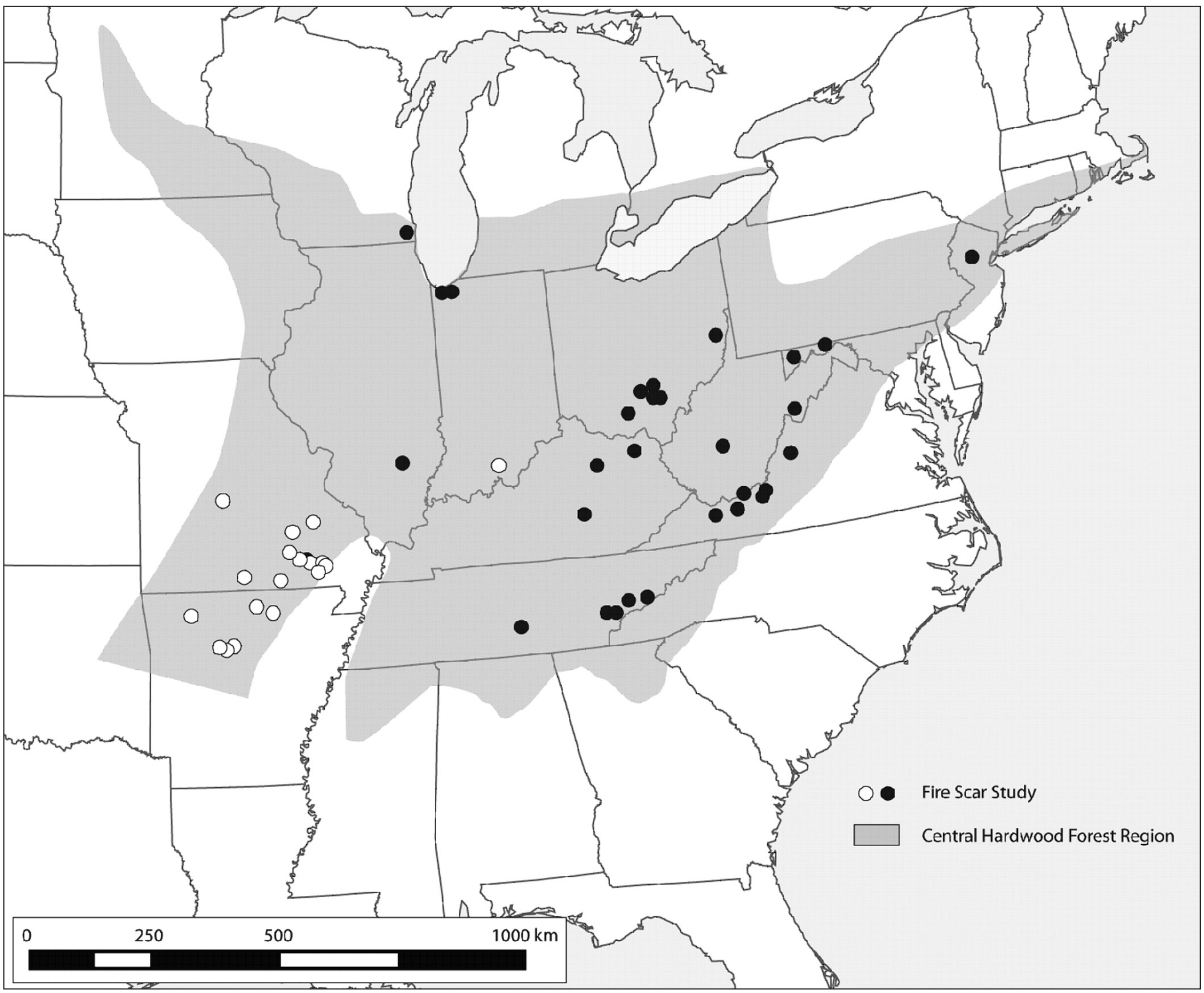

Figure 2.—Map of the Central Hardwood Forest Region (Fralish 2003, Fralish and Franklin 2002) and the location of sites with fire reconstructions based on dated fire scars in tree cross-sections. White circles represent temporally delineated fire history records that pre-date European settlement. Black circles represent all other fire scar records.

Missouri), but the mean initiation date for the total fire scar network is in the mid-1700s. Regional fire scar chronologies extend to the 17th century for 21 sites and to the 18th century for 50 sites, cumulatively. Approximately 35 percent of the fire scar records in the CHFR begin post-800. Fire frequency statistics of some form (e.g., mean fire return intervals) are available for the overwhelming majority of sites.

Table 3.—Descriptive data for fire scar based reconstruction sites from published studies in the Central Hardwood Forest Region. Only time periods with provided mean fire interval (MFI) values are reported. All MFI values are rounded to the nearest integer.

Reference	State	Period of record	MFI
Jenkins and others 1997	AR	1770-1993	6
Guyette and Spetich 2003	AR	1680-1820	5
		1821-1880	3
		1881-1920	5
Guyette and Spetich 2003	AR	1680-1820	16
		1821-1880	3
		1881-1920	2
Guyette and Spetich 2003	AR	1680-1820	13
		1821-1880	2
		1881-1920	1
Guyette and others 2006b	AR	1810-1830	2[†]
		1821-1880	2[†]
		1881-1920	2[†]
Guyette and others 2006b	AR	1810-1830	1[†]
		1821-1880	2[†]
		1881-1920	2[†]
Guyette and others 2006b	AR	1810-1830	2[†]
		1821-1880	4[†]
		1881-1920	5[†]
Stambaugh and Guyette 2006	AR	1670-1820	8
		1821-1880	2
		1881-1920	3
Engbring and others 2008	AR	1820-1900	2
		1901-1930	2
		1931-2003	3
McClain and others 2010	IL	1776-1850	2
		1851-1884	No fires
		1885-1996	1
Guyette and others 2003a	IN	1693-1801	No fires
		1888-1929	2
Henderson and Long 1984	IN	1929-1981	5
Henderson and Long 1984	IN	1933-1981	2
Cole and Taylor 1995	IN	1900-1990	5
McEwan and others 2007b	KY	1885-1954	9
McEwan and others 2007b	KY	1893-1954	12
McEwan and others 2007b	KY	1879-1900	2
Shumway and others 2001	MD	1616-1992	8[†]
Guyette and Cutter 1991	MO	1710-1810	4
		1810-1989	6
Guyette and Cutter 1997	MO	1821-1940	5
Guyette and Cutter 1997	MO	1581-1700	10
		1701-1820	3
		1821-1940	4
Guyette and Cutter 1997	MO	1581-1700	8
		1701-1820	4
		1821-1940	4
Guyette and Cutter 1997	MO	1701-1820	9
		1821-1940	3
Guyette and Cutter 1997	MO	1581-1700	6
		1701-1820	5
		1821-1940	5
Guyette and Cutter 1997	MO	1581-1700	30
		1701-1820	7
		1821-1940	2
Guyette and Cutter 1997	MO	1701-1820	9
		1821-1940	2
Guyette and Cutter 1997	MO	1581-1700	30
		1701-1820	13
		1821-1940	4
Guyette and Cutter 1997	MO	1581-1700	21
		1701-1820	13
Guyette and Cutter 1997	MO	1701-1820	11
		1821-1940	2
Guyette and Cutter 1997	MO	1581-1700	>37
		1701-1820	4
		1821-1940	2
Guyette and Cutter 1997	MO	1581-1700	12
		1701-1820	3
		1821-1940	2
Guyette and Cutter 1997	MO	1701-1820	12
		1821-1940	4
Guyette and Cutter 1997	MO	1701-1820	6
		1821-1940	2
Guyette and Cutter 1997	MO	1581-1700	19
		1701-1820	6
		1821-1940	3
Guyette and Cutter 1997	MO	1701-1820	13
		1821-1940	4
Guyette and Cutter 1997	MO	1701-1820	20
		1821-1940	5
Guyette and Cutter 1997	MO	1581-1700	7
		1701-1820	6
		1821-1940	2
Guyette and Cutter 1997	MO	1701-1820	16
		1821-1940	7
Guyette and Cutter 1997	MO	1701-1820	>45
		1821-1940	4
Guyette and Cutter 1997	MO	1701-1820	>50
		1821-1940	8
Guyette and Cutter 1997	MO	1701-1820	9
		1821-1940	6

[†]Weibull median or Weibull modal fire interval

(Table 3 continued on next page)

Table 3 (continued).—Descriptive data for fire scar based reconstruction sites from published studies in the Central Hardwood Forest Region. Only time periods with provided mean fire interval (MFI) values are reported. All MFI values are rounded to the nearest integer.

Reference	State	Period of record	MFI
Guyette and Cutter 1997	MO	1701-1820	10
		1821-1940	4
Guyette and others 2003b	MO	1700-1780	10
		1781-1820	3
		1821-1850	2
		1851-1890	2
		1891-1940	3
Guyette and others 2003b	MO	1700-1780	16
		1781-1820	4
		1821-1850	1
		1851-1890	1
		1891-1940	2
Guyette and others 2003b	MO	1700-1780	13
		1781-1820	3
		1821-1850	3
		1851-1890	2
		1891-1940	6
Guyette and Dey 1997a	MO	1700-1820	7
		1821-1930	2
Guyette and Dey 1997b	MO	1701-1820	6
		1821-1900	3
Stambaugh and others 2005	MO	1634-1780	22
		1780-1850	2
		1851-1930	2
Cutter and Guyette 1994	MO	1740-1850	3
		1850-1991	24
Guyette and Stambaugh 2004	MO	1604-1700	7
		1701-1820	4
		1821-1940	4
Dey and others 2004	MO	1705-1830	4
		1831-1960	8

Reference	State	Period of record	MFI
Buell and others 1954	NJ	1627-1950	>10
McCarthy and others 2001	OH	1624-1997	2
McEwan and others 2007b	OH	1917-1936	2
McEwan and others 2007b	OH	1875-1934	8
McEwan and others 2007b	OH	1878-1931	7
McEwan and others 2007b	OH	1900-1936	9
McEwan and others 2007b	OH	1889-1931	6
McEwan and others 2007b	OH	1889-1931	5
Hutchinson and others 2008	OH	1855-1935	9
Hutchinson and others 2008	OH	1858-1935	9
Hutchinson and others 2008	OH	1844-1935	15
Sutherland 1997	OH	1856-1995	5
Guyette and Stambaugh 2005	TN	1740-2002	5
Armbrister 2002	TN	1837-1934	7
Feathers 2010	TN	1685-2008	6
Feathers 2010	TN	1678-2008	3
Harmon 1982	TN	1856-1940	13
Laforest and others 2007	TN	1836-1929	7
Aldrich and others 2010	VA	1704-2003	5-17
DeWeese 2007	VA	1779-1934	3
DeWeese 2007	VA	1758-1934	4
DeWeese 2007	VA	1810-1934	2
DeWeese 2007	VA	1789-1934	3
Hoss and others 2008	VA	1794-2005	3
Sutherland 1993	VA	1765-1993	9-11
Wolf 2004	WI	1829-1839	4
		1840-1871	20
		1871-2004	5
Maxwell and Hicks 2010	WV	1898-2005	5
Schuler and McClain 2003	WV	1846-2002	18

Similar to the soil and sedimentary charcoal based fire networks, the fire scar based network is spatially clustered within certain subregions of the CHFR (Fig. 2). While both charcoal-derived records are concentrated in the Appalachian Highlands, over half of the published fire scar based histories have been focused in the Interior Highlands. Of all states that occupy a portion of the CHFR, Missouri has the highest number of site-specific fire scar reconstructions followed by Ohio (Table 3). A total of 12 states which comprise a portion of the CHFR have at least one fire scar based reconstruction. The Appalachian Plateaus (Mixed Mesophytic Forest Subdivision) and the Ridge and Valley (Appalachian Oak Forest Subdivison) provinces had the second and third highest occurrences of fire scar reconstructions. The longest fire scar records were reported from the Interior Highlands, with a mean record initiation date in the late-1600s (the oldest being 1581). The Appalachian Plateaus region supported the shortest fire records with a mean fire chronology start date in the mid-1800s (although the longest record for the province extended to 1616).

Of all site-specific fire scar datasets, slightly more than half report a temporally delineated fire frequency record based on human settlement and land-use patterns. Temporal delineation allows for comparisons between periods with different human population densities and land-uses, factors which are major influences on historic fire regimes (Guyette and others 2002, Guyette and Spetich 2003). Throughout the CHFR, indeed throughout the eastern United States, population density has widely fluctuated over the last four centuries. Within the depth of record afforded by fire scar analysis, changes in human population density and fire are commonly represented by four periods: 1) Native American depopulation (ca. mid-1500s to 1800); 2) Native American repopulation (not a full recovery but population increase above the minimum) and early European settlement (ca. 1800 to 1850); 3) widespread European settlement (ca. 1850 to 1930); and 4) fire suppression (ca. 1930 to present). The timing of these events differed between regions (Denevan 1992, Millner and others 2001, Ramenofsky 1987).

Decimation of Native American populations by the spread of alien contagious infectious diseases in the eastern United States began as early as the 16th century in the Mississippi River Valley but was not widespread throughout the region until the mid-17th century (Denevan 1992, Millner and others 2001, Ramenofsky 1987). The timing of widespread European settlement and intensive land use also differed significantly between regions. For example, areas of the mid-Atlantic, the Northeast, and portions of Kentucky and Ohio were settled by 1800 whereas broad-scale settlement of the eastern United States was not complete until 1850 (Gerlach 1970). In fact, widespread European settlement on the Cumberland Plateau, located only ca. 550 km from major eastern port cities, did not occur until well into the 1800s. In summary, the commonly used temporal designations are site-specific based on local population densities and culture. Of the common temporal delineations, only the onset of the fire suppression period has a largely static date (between 1920 and 1940).

Within the CHFR fire scar record, 25 sites provide explicit fire data for portions of the Native American depopulation period. The overwhelming majority of records that extend to this period are located in Missouri and Arkansas. This period is characterized by relatively long fire-free intervals. For example, during the Native American depopulation period, no fires were recorded for over a century in an Indiana barren (Guyette and others 2003a), and the mean fire return interval (MFI) was more than 37 years in a Missouri hardwood savanna (Guyette and Cutter 1997). The vast majority of the temporally delineated records that extend to this period display longer fire return intervals as compared to the subsequent period of repopulation and early European settlement. This pattern has been explained by low human population density and thus fewer ignitions. However, this pattern was not evident in two Appalachian Highland fire reconstructions. Shumway and others (2001) sampled on side slopes of Savage Mountain in western Maryland and obtained a fire scar record extending to 1616. The authors did not find differences in fire importance between the pre-European and post-European settlement periods. They mention direct evidence of Native American activity downslope from the sample sites. During the period of aboriginal depopulation, Native American settlements were sparsely scattered throughout the eastern United States (Millner and others 2001). It is therefore possible that the sample site was located near a Native American settlement location that was not completely eradicated by the infectious diseases that decimated a majority of Native American populations in the region. Aldrich and others (2010) reconstructed fire history at Mill Mountain, a xeric ridgetop site in the Ridge and Valley of Virginia. Similar to Shumway and others (2001), the fire regime did not differ significantly between the pre-European and post-European settlement periods. However, throughout the extent of the record (beginning ca. 1700), European influence was documented in the area (e.g., hunting, trading, and raiding parties), and the site was then settled in the mid-1700s. Therefore, these pre-European settlement fires may have been either anthropogenic ignitions or natural ignitions from terrain-induced thunderstorms during dry conditions (Aldrich and others 2010), a distinction that is indiscernible in the fire scar record alone. Though this study is beneficial for understanding ridgetop pine-oak communities in the Central Appalachians, the findings may not be representative of the broader eastern oak forest region.

The Native American repopulation and early European settlement period is short (e.g., some studies classify this period as lasting 20 years), variable, and not used in all fire reconstructions. Aboriginal populations rebounded from the decimation at different speeds (Denevan 1992, Ramenofsky 1987). Similarly, early European settlement was variable in extent and intensity. Generally, fire during this period was more frequent than the preceding depopulation period but less frequent than the subsequent period of widespread European settlement. The fire return intervals during this transitional period were variable and typically ranged from a low of 1 to a high of 12 years between fire events. Two studies in the Central Lowlands documented anomalous fire histories during the early European settlement period. McClain and others (2010) and Wolf (2004) documented fire-free periods at the onset of early European settlement. This pattern was attributed to a purposeful avoidance of fire by European settlers as they feared destruction of crops, fences, buildings, and other property (McClain and others 2010).

During widespread European settlement, the spatial extent and intensity of human impacts on forest communities increased throughout the eastern United States (Cronon 1983, Motzkin and others 1999, Whitney 1994). This period was typified by frequent fires, more frequent than those during the preceding periods. Indeed, many studies documented fire return intervals as short as 1 to 3 years. In contrast to many presettlement fires, fires during this period were typically smaller in extent because of fuel fragmentation and fire breaks (Guyette and others 2002). However, Shumway and others (2001) found that presettlement fires were smaller in relative extent but greater in relative intensity than postsettlement fires. This period of frequent fire ended in the early 20th century with the onset of active fire suppression.

Regional patterns of fire occurrence are difficult to discern because many records are not temporally delineated, include depopulation and fire suppression periods, and fire histories are site specific. However, some general spatial trends are evident. As compared to eastern portions of the CHFR, fire return intervals were generally shorter in the western portions of the region. Many studies conducted in the western portions documented fire return intervals of less than 3 years with some annual fires. In contrast, the mean fire return interval in eastern portions was ca. 7 years with some longer fire free intervals. Again, we stress that fire histories are site specific and that, with the distribution of fire scar studies, this comparison is largely between the Interior Highlands and the Appalachian Highlands.

SYNTHESIS OF FIRE HISTORY

Elucidation of broadscale historical fire regime characteristics in the CHFR was difficult because each of the reviewed biological archives provided information with different spatial and temporal resolutions. Nonetheless, some general patterns could be gleaned from these records. Based on charcoal data, fire frequency in the CHFR increased during cultural transition periods (i.e., from Archaic to Woodland and from Woodland to Mississippian). These results could be interpreted that fire return intervals were shorter during these transition periods, that fire was more widespread, or both. Regardless, the increase in fire (as evidenced by an increased in charcoal) during these periods may have resulted in long-lasting legacies in some oak ecosystems. The fire scar record provided more detailed fire history information, albeit over a shorter period of history. In general, fire-free intervals were longest during the Native American depopulation period. Fire was more common during the Native American repopulation and early European settlement period, but did not drastically increase until the period of widespread European settlement. Many studies during the widespread European settlement period revealed MFIs of 1 to 3 years. These fires were typically smaller in extent than those of prior periods because of fire breaks caused by forest fragmentation. This trend illustrated the influence of human population density and land use, which differed by culture, on fire regimes. Certainly there were exceptions to these general trends, and notably some of the outliers were clustered spatially in distinct physiographic provinces. We suggest fire historians continue to analyze temporally delineated fire history characteristics. The dates of cultural milestones (e.g., European settlement) differ across the CHFR, and site-specific temporal delineations allow for comparison of historical periods across a multitude of sites and thus, allow for a clearer interpretation of broadscale trends. Without question, additional fire histories developed from each of these archives are needed to understand past fire regimes and the influence of those events on oak ecosystems, especially in regions where fire reconstructions are sparse or on site types where fire history is poorly understood (e.g., mesic and submesic sites).

RESTORATION IMPLICATIONS

Ecological restoration is the act of returning an ecosystem to a prior state (Egan and Howell 2001). The practice of restoration implies that the site has been degraded and that the previous condition is more desirable based on management goals (Swetnam and others 1999). Fire has been incorporated into a variety of restoration plans (Pyke and others 2010) as prescribed fires can be used in structure- or process-based restoration activities (Parsons and others 1986, Swetnam and others 1999, Vale 1987). In the former, fire is used as a silvicultural tool much like thinning or herbicide application to shape species composition and stand structure to that of the target reference conditions (Brose and others 2001). In the latter, prescribed fire is used to mimic historical disturbance from an identified time period (e.g., aboriginal burning) (Brose and others 2001). Certainly, prescribed fire is being used by forest managers for purposes other than ecological restoration. However, if fire is to be used in ecological restoration to achieve management goals, certain procedures should be regarded. First, a reference model should be developed by identifying a discrete time period that represents the desired conditions for the site (Landres and others 1999). Second, managers should implement a multi-proxy reconstruction of site history using cultural and biological archives. During this process, the historic range of variability (HRV), which is the range of conditions within which ecosystems are in dynamic equilibirum, should be quantified as it provides the restoration targets (Egan and Howell 2001, Swetnam and others 1999). The HRV refers to both pattern and process and incorporates many variables including composition and structure measures and information regarding disturbance type, frequency, extent, and magnitude. Third, a silvicultural prescription should be developed to restore the site to the target conditions (i.e., within the HRV). Fire can be implemented as either a structure- or process-based treatment. Finally, criteria should be developed to monitor restoration success (Egan and Howell 2001). While reference models can be developed using ecological theory or environmental reconstructions, results from the published studies reviewed in this manuscript reveal that fire histories are site specific. Therefore, managers focused on ecological restoration are best advised to construct a place-based history and not rely on results from other studies alone to set restoration targets and monitor treatment success.

ACKNOWLEDGMENTS

We thank R. Pine, S. Rhine, J. Richards, and C. Turberville for assistance with locating published fire histories. We also thank the many contributors to the fire history network in the Central Hardwood Forest Region, and we apologize for missing works.

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