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The Fire–Oak Literature of Eastern North America: Synthesis and Guidelines

Patrick H. Brose
Daniel C. Dey
Thomas A. Waldrop

Forest Service | Northern Research Station | General Technical Report NRS-135 | July 2014

Abstract

Guidelines for using prescribed fire to regenerate and restore upland oak forests, woodlands, and savannas in eastern North America were developed by synthesizing the results of more than 100 scientific publications. The first four chapters provide background information on the values of oak ecosystems, eastern fire history, oak's adaptations to fire, and the findings of fire-oak research conducted over the past 50 years. The final chapter synthesizes that background information into guidelines that explain how to use prescribed fire to facilitate oak seedling establishment, release oak reproduction from competing mesophytic hardwoods, and rehabilitate open oak woodlands, oak savannas, and scrub oak communities. A reference section is also provided for readers desiring to delve more deeply into the associations between periodic fire and oak forests, woodlands, and savannas.

The Authors

PATRICK H. BROSE is a research forester with the U.S. Forest Service, Northern Research Station, Irvine, PA.

DANIEL C. DEY is a research forester and project leader with the U.S. Forest Service, Northern Research Station, Columbia, MO.

THOMAS A. WALDROP is a research forester and team leader with the U.S. Forest Service, Southern Research Station, Clemson, SC.

Cover Photos

Photos illustrating two of the roles that periodic prescribed fire can fulfill in the sustaining of mixed-oak forests in eastern North America. Upper left: oak forest succeeding to a mixed mesophytic forest in the absence of periodic fire. Upper right: seedbed preparation burn in a mature oak stand. Lower left: release burn in an oak shelterwood. Lower right: oak stand with abundant, vigorous oak reproduction resulting from the use of prescribed fire. Photos by Patrick Brose and Daniel Yaussy, U.S. Forest Service.

This synthesis was funded by the Joint Fire Science Program

Manuscript received for publication 27 December 2013

Published by:

U.S. FOREST SERVICE
11 CAMPUS BLVD SUITE 200
NEWTOWN SQUARE PA 19073

July 2014

For additional copies:

U.S. Forest Service
Publications Distribution
359 Main Road
Delaware, OH 43015-8640
Fax: (740)368-0152
Email: nrspubs@fs.fed.us

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This publication conforms to the Northern Research Station's Quality Assurance Implementation Plan which requires technical and policy review for all scientific publications produced or funded by the Station. The process included a blind technical review by at least two reviewers, who were selected by the Assistant Director for Research and unknown to the author. This review policy promotes the Forest Service guiding principles of using the best scientific knowledge, striving for quality and excellence, maintaining high ethical and professional standards, and being responsible and accountable for what we do.

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CHAPTER 1: INTRODUCTION

Of all the plant communities that make up the eastern hardwood biome, the oak[1] ecosystems (forests, savannas, shrublands, and woodlands) are perhaps the most important because of their vastness, diversity, and many ecological and economic values (Smith 2006). At least 50 oak species grow east of the 100th meridian, and some type of oak community is found in every state and adjacent Canadian province (Burns and Honkala 1990, Stein et al. 2003). Some oak species such as white oak are widespread and occur in most states and provinces, while others like Mohr oak are restricted to a few counties in Oklahoma and Texas. Oaks occur as solitary individuals in grassland environments, as a few scattered trees in northern hardwood forests, as substantial portions of complex, mixed-species assemblages, and as nearly pure monocultures (Fig. 1). They vary in size from the shrubby runner oak and vine-like dwarf live oak to the massive bur oak and cherrybark oak. Oaks grow in a wide array of habitats, from seasonally-flooded bottomlands, to rich mountain coves, to xeric ridges and sandhills. Their widespread occurrence, variation in size and form, and diversity of habitats are three of the reasons the generic oak was designated by Congress as America's national tree (Arbor Day Foundation 2001, 2004).

[1] Scientific names of flora and fauna are listed in the Appendix.

Figure 1.—Oaks occur as solitary trees (upper left), scattered individuals in other forest types (upper right), substantial portions of mixed-species stands (lower left), and as nearly pure monocultures (lower right). Photos by Patrick Brose, U.S. Forest Service.

Figure 2.—In many parts of eastern North America, oak forests are being replaced by various mesophytic hardwood species such as red maple. Photo by Patrick Brose, U.S. Forest Service.

Despite this widespread occurrence and dominance, oak ecosystems are declining in abundance and require careful management to be sustained. The scientific literature abounds with studies reporting chronic oak regeneration failures and the replacement of oaks by mesophytic hardwood species (Abrams and Downs 1990, Aldrich et al. 2005, Healy et al. 1997, Schuler and Gillespie 2000, Woodall et al. 2008). Pennsylvania is a prime example of the oak regeneration problem. Recent U.S. Forest Service Forest Inventory and Analysis data show that for all stems larger than 2 inches in diameter at breast height (d.b.h.), red maple and sweet birch are the two most common species, and the most common oak, northern red, is the ninth most abundant hardwood (McWilliams et al. 2004). The disparity is especially evident in the sapling (1- to 5-inch d.b.h.) and pole (6- to 10-inch d.b.h.) size classes where red maple outnumbers all oaks by ratios of 6:1 and 3:1, respectively (Fig. 2). As mature oaks succumb to various causes, they are being replaced by hardwood species other than oaks. This conversion is highly undesirable for many ecological and economic reasons.

The Values of Oak Ecosystems

One of the primary reasons for retaining and promoting oak is its importance to wildlife, and that value begins with the foliage. Oaks produce copious amounts of foliage, and these leaves are the base of the food chain in the eastern hardwood biome. Among the genera of woody plant species native to the mid-Atlantic region, oak ranks first in the ability to support native butterfly and moth (Lepidoptera) species (Fig. 3) (Tallamy and Shropshire 2009). The authors documented that the larva of 534 native lepidopteran species consume oak leaves. These larvae serve as food for other insects, birds, and small mammals (Fig. 4). Birch and maple, common oak-replacement trees, support considerably fewer native lepidopteran species. In addition to foliage, oak bark supports insects of all types because the rough texture provides refuge from

Figure 3.—The orangestriped oakworm is one of the 534 native lepidopteran species that feed on oak foliage. Photo by Kurt Gottschalk, U.S. Forest Service.

Figure 4.—Cerulean warblers (top left), scarlet tanagers (top right), and red-eyed vireos (bottom left) are three neotropical migrant songbirds that make extensive use of oak ecosystems and the caterpillars found there. Photos by Scott Stoleson, U.S. Forest Service.

Figure 5.—The rough bark of oak trees such as chestnut oak (left) serves as refuge for many insect species. The smooth bark of many mesophytic species such as red maple (right) lack this protective attribute. Photos by Patrick Brose, U.S. Forest Service.

predators and weather compared to the smooth bark of birches and maples which provide little, if any, protection (Fig. 5). When comparing bird densities between mature stands dominated by oak or red maple, Rodewald and Abrams (2002) found that oaks support a significantly higher abundance of birds in all seasons. In addition, avian species richness is significantly greater in oak than in maple stands. Differences are greatest in autumn during masting and in spring when oak flowers attract insects. They predict that a conversion of oak forests to red maple would have a severe impact on bird communities in the eastern United States. In aquatic environments, oak leaves are a valuable source of detritus that directly and indirectly benefits numerous organisms (Rubbo and Kiesecker 2004).

The longevity and size of oaks are important to wildlife. Many of the oaks are long-lived, quite resistant to rot, and grow to large sizes. These characteristics indicate that, once established, oak forests are relatively stable plant communities (Smith 2006). Once oaks achieve canopy dominance, they likely will persist for decades to centuries as they readily withstand insect outbreaks, lightning strikes, wind events, and ice storms. When damage does occur, the ability to compartmentalize rot helps ensure their continued survival (Shigo 1984). When oaks are injured, the injury sites may become cavities which, in turn, become dens for wildlife. Dens are especially valuable as wildlife habitat when they occur in large trees (Godfrey et al. 2000).

Another structural characteristic that makes oaks important to wildlife is their broad, open crowns (Fig. 6). The canopies of oak forests and woodlands are usually uneven (vary in height and thickness), discontinuous (have small gaps between adjacent crowns), and contain large branches. This canopy heterogeneity is important habitat for bats and crown-nesting birds like

Figure 6. —The broad, open crowns of many mature oaks are important to bats and some neotropical bird species, especially in woodlands and savannas. Photo by Patrick Brose, U.S. Forest Service.

Figure 7. —The understory of many oak forests has the necessary light level to support a rich herbaceous plant community. Photo by Patrick Brose, U.S. Forest Service.

the cerulean warbler. Hamel et al. (2004) reported that cerulean warblers nest and forage more in oak forests than mixed hardwood forests. Oak canopies are also easily penetrated by sunlight which allows the development of diverse herbaceous and shrub communities (Fig. 7) that provide further food and habitat for wildlife.

Acorns only occur intermittently but are a valuable food resource for many animals because they are relatively large, readily digestible, easily stored, and high in nutrition (Kirkpatrick and Pekins 2002, McShea and Healy 2002). Within the eastern hardwood biome, more than 100 vertebrate species regularly consume acorns, ranging from important game animals such as white-tailed deer, black bear, tree squirrels, wild turkey, wood ducks, and ruffed grouse, to nongame species such as red-headed woodpeckers, blue jays, white-footed mice, and chipmunks. In the Appalachians and the Northeast, acorns are the primary source of hard mast since the loss of the American chestnut and the decline of American beech.

In oak ecosystems, many species of wildlife depend on acorns to such an extent that they exhibit physiological and population responses to fluctuations in acorn crops. For example, acorn availability can affect the weight, condition, reproductive rates, and antler characteristics of white-tailed deer (Wentworth et al. 1992). Similarly, rates of birth, survival, and dispersal in black bear vary with the abundance and distribution of acorn crops (Pelton 1989). Variation in mast production also influences population levels and distributions of a variety of small mammals and birds, including squirrels, jays, and woodpeckers (McShea 2000, Rodewald 2003).

Oak species are of great economic importance to the eastern United States and Canada. The stumpage price for oak consistently ranks near or at the top among all commercial hardwood species. Oak saw logs are used for a variety of products ranging from cabinets, fine furniture, flooring, and whiskey barrels to dimension lumber, pallets, and railroad ties (Fig. 8). The wood-products industry employs thousands of people in the eastern United States and Canada, a significant proportion of which is related to the growth, harvest, manufacturing, and delivery of products from oak.

Figure 8.—Oaks are renowned for their high quality timber (above) that serves as the raw material for a wide array of wood products (right). Photos by Patrick Brose, U.S. Forest Service.

The Fire-Oak Synthesis Project

The chronic, widespread oak regeneration problem is widely regarded by many natural resource professionals to be caused, at least in part, by the advent of fire exclusion policies in the early 1900s (Abrams 1992, Brose et al. 2001, Nowacki and Abrams 2008). The pervasiveness of the oak regeneration problem and the role of fire exclusion in it have sparked tremendous research interest in the fire-oak association by scientists over the past 50 years. This research focuses on understanding the history of fire, especially before European settlement, and the effects of fire on hardwood species and other ecosystem attributes. All of this research has produced a wide array of scientific articles ranging from simple case studies in conference proceedings to complex studies published in peer-reviewed journals.

In 2010, the Joint Fire Science Program (JFSP) issued a request for proposals to synthesize the existing fire-oak literature. The ultimate goal was to develop guidelines for using prescribed fire to restore and sustain upland oak ecosystems in eastern North America (defined as east of the 100th meridian). This opportunity was especially interesting to us because we all have been involved in fire-oak research for much of our careers, publishing numerous scientific papers on the subject, and frequently giving oral presentations to a wide variety of audiences. This report is the culmination of that literature synthesis and one of the products of the JFSP project.

This report is organized around the fire-oak hypothesis (Abrams 1992, Arthur et al. 2012, Brose et al. 2001, Nowacki and Abrams 2008) which consists of four parts:

1. Fire has been an integral part of upland oak ecosystems in eastern North America for millennia.
2. Oaks are superiorly adapted relative to other hardwoods to survive a periodic fire regime and exploit the postfire environment.
3. The cessation of a periodic fire regime in the early 1900s is a major cause for the current oak regeneration problem.
4. Prescribed fire can be used in some situations to help regenerate and restore upland oak ecosystems.

Chapter 2 addresses fire-oak hypothesis parts 1 and 3 by reviewing the fire history publications of the eastern hardwood biome. Chapter 3 covers part 2 of the fire-oak hypothesis and the silvical characteristics of oak that make it a superior survivor and competitor in a periodic fire regime. Chapter 4 reviews the published fire effects on oak reproduction and relates them to part 4 of the fire-oak hypothesis. Chapter 5 synthesizes the findings of these three chapters into guidelines on how to use prescribed fire in upland oak ecosystems to meet some common management objectives. An extensive reference section listing the papers used in this project is also provided.

CHAPTER 2: FIRE HISTORY OF EASTERN NORTH AMERICA

Parts 1 and 3 of the fire-oak hypothesis posit that periodic fire has been an integral disturbance in the upland oak ecosystems of eastern North America for millennia, and the sudden cessation of that fire regime is one of the major causes of the current oak regeneration problem (Abrams 1992, Arthur et al. 2012, Brose et al. 2001, Nowacki and Abrams 2008). Both of these premises have been the focus of historical research over the past 20 to 30 years. Generally, this research emphasizes cultural burning by American Indian tribes prior to European settlement and changes to this fire regime during and after European settlement.

For much of the 20th century, most ecologists did not consider fire to be a factor in the ecology of the eastern hardwood biome. Oosting (1942) does not mention fire in his analysis of plant communities of the Piedmont region nor does Braun (1950) mention fire in her book on the eastern hardwood forests. Whittaker (1956) surmised that fire played a role in hard pine[1] and shrub communities in the southern Appalachian Mountains but saw no role for it outside these environs. Concomitant with this dismissal of fire as an important ecological process was the belief that American Indian tribes had negligible impact on the eastern hardwood biome. Indians were believed to be ecologically invisible, living in harmony with nature in a vast forest that extended from the Atlantic Ocean to the Great Plains (Adams 1935, Bear 1951, Lillard 1947, Parkman 1909). However, early writings by European explorers, missionaries, and settlers revealed that many American Indian tribes routinely used fire for numerous reasons, especially close to their villages and travel paths (Day 1953, Denevan 1992, Hough 1926, Maxwell 1910). Unfortunately, historical writings cannot tell us about prehistoric (before written records) fires nor do they tell us much about the characteristics of the Indian-set fires.

To help understand prehistoric and Indian-set fires and how they varied by location and time in the eastern hardwood biome, we collected and reviewed 30 paleoecology (sediment/soil core) and 51 dendrochronology (fire scar) studies. Nearly all of these studies occurred in the past 20 years and have been published in a wide variety of outlets ranging from master's theses to high-quality, peer-reviewed journals. Because most all these studies are case histories (occur at just one site), statistical analysis is descriptive. In this chapter, we look for commonalities and trends that provide new insights into the fire regimes of upland oak ecosystems and are useful for managers and researchers.

Paleoecology Studies

Paleoecology studies create multi-millennial, coarse-scale chronologies of fire occurrence by examining the charcoal that accumulates in undisturbed forest soils and in the sediments of small, land-locked lakes. Soil or sediment cores are collected and carefully cut apart in distinct layers, and the charcoal fragments are extracted from the layers. The characteristics of the charcoal fragments give some indication of the fires that created them. Larger fragments (>2 mm in surface area) indicate a fire near the sampling site while smaller fragments suggest a fire farther away from the study area. Similarly, an abundance of charcoal fragments corresponds to a larger, more intense fire while small charcoal accumulations indicate a smaller, less intense

[1]Scientific names of the flora and fauna are listed in the Appendix.

fire. The charcoal can also be carbon dated to determine approximately when the fire occurred. In some cases, the position of the charcoal in the core can help diagnose the relative time of the fire. In the sediment studies, identification and quantification of plant pollen is usually part of the project as this indicates the dominant taxa near the research sites and changes in their relative abundance through time.

Of the 30 paleoecology studies, 18 were in the central/southern Appalachian Mountains region and the remainder was evenly divided between the Great Lakes and Northeast, with none occurring in the Midwest (Fig. 9). The chronologies of these studies ranged from 425 to 17,345 years with most of them producing chronologies of 2,000 to 4,000 years (Table 1). Charcoal is found throughout the samples indicating that fire has been a part of the environment for millennia. Generally, charcoal was the most abundant in the southern Appalachian sites and decreased in abundance to the north. This gradient likely reflects distribution of ancient human populations as well as climatic influences. There were more humans and warmer weather in the southern Appalachians than there were in the northern Appalachians. Temporally, charcoal increased through time, with marked increases at 4,000 years before present (YBP), 1,000 YBP, and 250 YBP. The two oldest dates correspond with the rise of Woodland and Mississippian Native American cultures and populations in eastern North America while the third marks the beginning of European settlement.

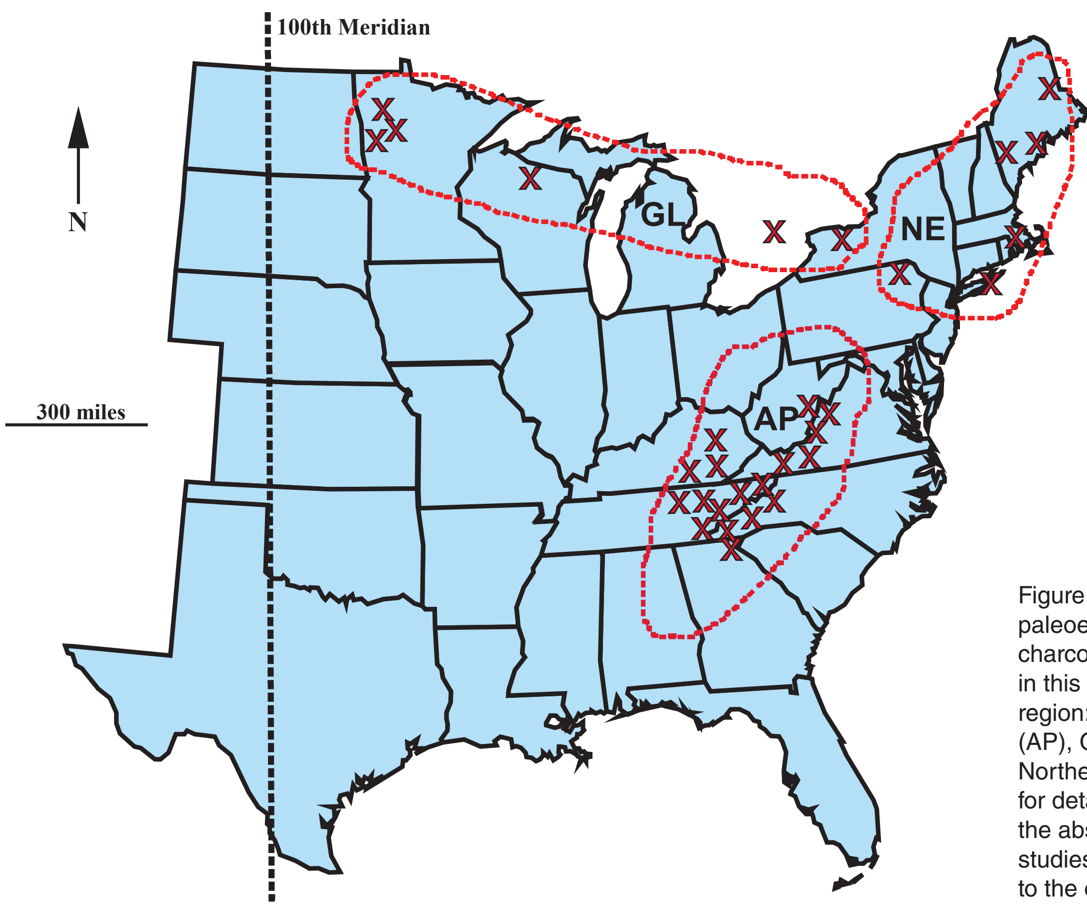

Figure 9.—Location of the paleoecology (sediment/soil charcoal) studies reviewed in this project grouped by region: Appalachian Mountains (AP), Great Lakes (GL), and Northeast (NE). See Table 1 for details of the studies. Note the absence of paleoecology studies in the Midwest relative to the other three regions.

Table 1.—Characteristics of the paleoecology studies reviewed in this project

Region[a]	State	Publication	Charcoal type	Chronology length (years)[b]
AP	GA, KY, NC,TN	Welch 1999	Soil	not determined
AP	NC	Delcourt and Delcourt 1997	Sediment	3,900
AP	KY	Delcourt et al. 1998	Sediment	9,500
AP	NC	Fesenmyer and Christensen 2010	Soil	4,000
AP	TN	Cridlebaugh 1984	Sediment	2,800 and 900
AP	TN	Haas 2008	Sediment	2,800 and 425
AP	TN	Hart et al. 2008	Soil	6,735
AP	VA	Kneller and Peteet 1993	Sediment	17,130
AP	VA	Kneller and Peteet 1999	Sediment	17,345
AP	VA	Patterson 2006	Sediment	6,000 and 900
AP	WV	White 2007	Sediment	8,180
GL	MN	Clark 1990	Sediment	750, 750, and 750
GL	NY	Clark and Royall 1996b	Sediment	10,400
GL	ONT	Clark and Royall 1995	Sediment	2,000
GL	WI	Clark and Royall 1996a	Sediment	2,400
NE	MA	Patterson 2006	Sediment	500
NE	ME	Clark and Royall 1996a	Sediment	1,700 and 1,900
NE	ME	Patterson 2006	Sediment	8,240
NE	NY	Patterson 2006	Sediment	2,180
NE	PA	Clark and Royall 1996a	Sediment	2,100

[a]AP = Appalachian Mountains, GL = Great Lakes, and NE = Northeast.
[b]Multiple chronologies for a publication indicate that the paper reports data from two or more neighboring sites.

Dendrochronology Studies

Dendrochronology studies construct multi-decadal to multi-century, fine-scale chronologies from the basal scars that form on living trees when a fire kills a portion of the cambial tissue (Fig. 10). Methodology is simple and straight forward for fire scar research. A partial or complete cross section is cut from a scarred tree or snag using a chainsaw. The cross section is then sanded to reveal the annual rings and the scars (Fig. 11). A calendar year is then assigned to the annual rings and scars using standard dating techniques (Speer 2010).

Overall, the 51 fire scar studies were spread throughout the eastern hardwood biome. They occurred in 20 states and 1 Canadian province (Fig. 12, Table 2). On average, a study consisted of 49 sample trees that produced a 276-year chronology spanning from 1689 to 1965 (Table 3). In that period, an average of at least 53 fires occurred. This is a conservative estimate because it is possible for a fire to burn and not scar trees or have its evidence erased by a later fire or decay. The mean fire intervals (MFIs, the time between successive fires) varied through time. Prior to European settlement, fires burned about once every 13 years. With settlement, fire frequency increased to once every 7 years. After modern fire exclusion policies began, fire frequency subsided to once every 46 years. Regardless of the time period, most fires occurred during the dormant season when the trees were not actively producing radial growth.

Figure 10.—A "catface" on the uphill side of a mature red pine that probably formed in response to fire damage. Photo by Patrick Brose, U.S. Forest Service.

Figure 11. —A sanded cross section of a red pine showing the annual rings and dated fire scars. Photo by Patrick Brose, U.S. Forest Service.

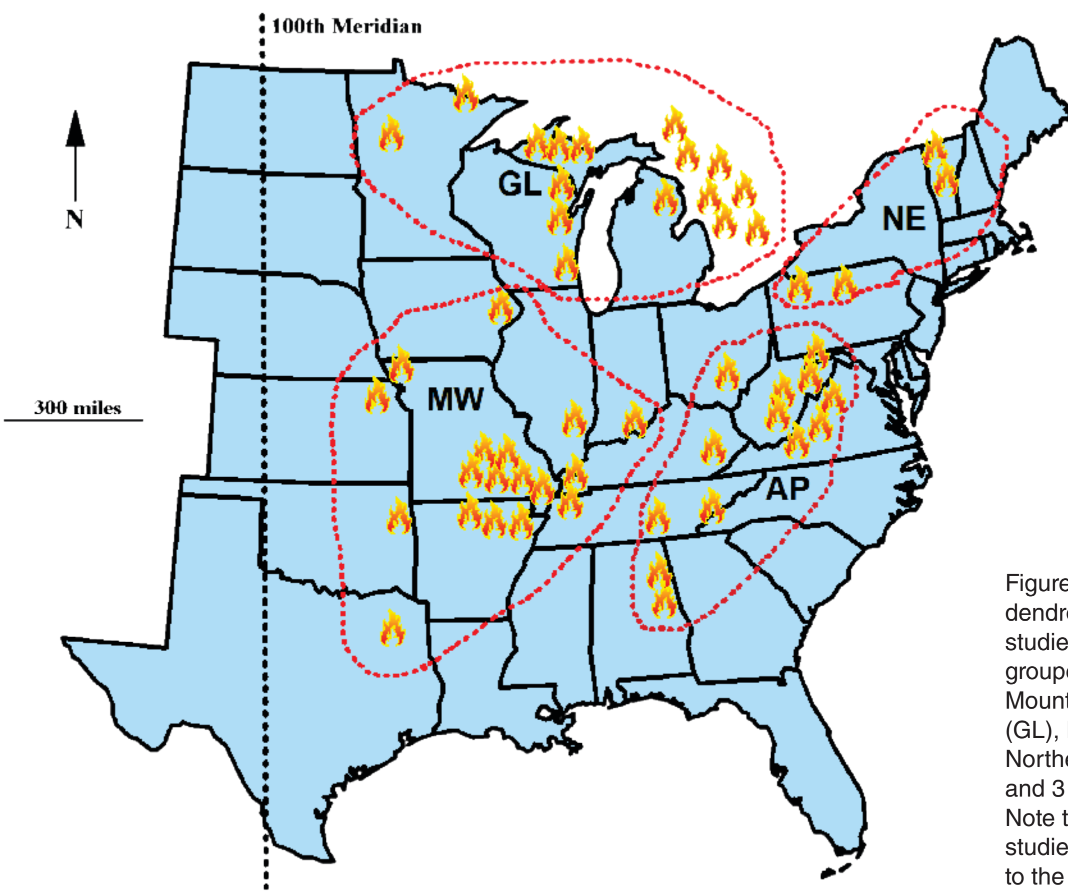

Figure 12.—Location of the dendrochronology (fire scar) studies reviewed in this project grouped by region: Appalachian Mountains (AP), Great Lakes (GL), Midwest (MW), and Northeast (NE). See Tables 2 and 3 for details of the studies. Note the scarcity of fire scar studies in the Northeast relative to the other three regions.

Table 2.—Characteristics of the fire scar studies reviewed in this project

Region[a]	State	Publication	Recorder species	Sample size	Chronology years	Fire years	Pre-MFI[b] (years)	Post-MFI (years)	Mod. MFI (years)	Season of burn[c]
AP	AL	Guyette et al. 2009	Longleaf pine	24	1550-1940	106	2.7	2.6	75.0	DS
AP	AL	Guyette et al. 2009	Longleaf pine	26	1547-2006	113	3.2	2.5	4.2	DS
AP	KY	Guyette et al. 2009	Upland pines	31	1742-2005	38	6.3	3.7	85.0	DS
AP	MD	Shumway et al. 2001	White oak	20	1600-2000	42	8.8	8.0	100.0	DS
AP	OH	Hutchinson et al. 2008	White oak	137	1870-1984	28	?[d]	4.7	24.3	DS
AP	TN	Armbrister 2002	Upland pines	9	1776-2000	37	7.5	6.7	15.3	n.d.
AP	VA	Aldrich et al. 2010	Upland pines	63	1704-2003	42	6.0	5.0	30.0	DS
AP	VA	Hoss et al. 2008	Upland pines	73	1794-2005	53	?	2.1	4.3	DS
AP	VA	Lafon et al. 2006	Upland pines	172	1700-2000	227	6.4	3.5	7.4	DS
AP	WV	Hessl et al. 2011	Upland pines	36	1868-1953	9	?	8.3	55.0	DS
AP	WV	Maxwell and Hicks 2010	Upland pines	21	1898-2005	25	?	3.0	5.0	DS
AP	WV	Schuler and McClain 2003	Northern red oak	17	1846-2002	7	?	13.3	28.0	n.d.
GL	MI	Drobyshev et al. 2008	Red pine	248	1707-2006	217	28.5	14.3	20.0	GS
GL	MI	Guyette et al. 2009	Red pine	30	1494-1914	27	10.2	6.4	?	DS
GL	MI	Guyette et al. 2009	Red pine	38	1500-2000	19	31.2	11.7	100.0	GS
GL	MI	Guyette et al. 2009	Red pine	23	1600-2000	11	41.4	17.2	100.0	GS
GL	MN	Frisell 1973	Red pine	?	1650-1922	32	14.6	6.1	50.0	n.d.
GL	MN	Heinselman 1973	Red pine	178	1542-1972	71	19.7	3.3	15.0	GS
GL	ONT	Cwynar 1977	Red pine	?	1696-1960	25	22.8	8.7	50.0	GS
GL	ONT	Dey and Guyette 1996a	White pine	32	1721-1937	14	10.8	12.7	100.0	n.d.
GL	ONT	Dey and Guyette 1996b	White pine	15	1689-1849	9	22.5	?	?	n.d.
GL	ONT	Dey and Guyette 1996c	White pine	18	1634-1875	7	25.2	?	?	n.d.
GL	ONT	Guyette and Dey 1995a	Red pine	26	1665-1780	8	14.0	?	?	n.d.
GL	ONT	Guyette and Dey 1995b	Red pine	18	1636-1994	11	28.3	22.5	64.0	n.d.
GL	ONT	Guyette et al. 1995	White pine	13	1700-1850	15	8.3	?	?	n.d.
GL	WI	Guyette et al. 2009	Red pine	28	1706-2005	24	6.5	19.7	75.0	DS
GL	WI	Guyette et al. 2009	Red pine	15	1705-1870	24	8.6	6.0	?	DS
GL	WI	Wolf 2004	White oak	16	1804-2000	57	4.5	8.6	4.0	GS
MW	AR	Engbring et al. 2008	Shortleaf pine	94	1823-2002	61	?	2.0	2.6	n.d.
MW	AR	Guyette and Spetich 2003	Shortleaf pine	45	1670-2000	171	11.2	2.8	80.0	DS
MW	AR	Stambaugh and Guyette 2006	Shortleaf pine	26	1725-2001	92	7.7	2.1	4.0	DS
MW	IA	Guyette et al. 2009	White oak	20	1699-1860	20	5.0	?	?	DS
MW	IL	McClain et al. 2010	Post oak	36	1770-1996	118	2.0	1.4	2.5	n.d.
MW	IN	Guyette et al. 2003	Post oak	27	1654-1999	41	23.0	5.3	7.6	n.d.
MW	KS	Abrams 1985	Bur oak	19	1862-1983	23	?	15.7	?	n.d.
MW	KY	Guyette et al. 2009	Post oak	36	1688-2005	46	9.0	4.2	60.0	DS
MW	MO	Cutter and Guyette 1994	Post oak	24	1734-1991	45	2.7	8.3	30.0	n.d.
MW	MO	Guyette and Cutter 1991	Post oak	47	1656-1989	43	4.3	6.4	12.5	DS
MW	MO	Guyette and Cutter 1997	Shortleaf pine	168	1558-1993	41	15.5	3.7	4.8	DS
MW	MO	Guyette and Dey 1997	Shortleaf pine	9	1695-1930	67	7.1	2.2	75.0	n.d.
MW	MO	Guyette and Stambaugh 2000	Shortleaf pine	12	1604-1996	81	5.7	3.7	4.8	DS
MW	MO	Stambaugh et al. 2006	Bur oak	33	1671-2004	60	6.6	1.6	25.0	DS

continued

Table 2.—continued

Region[a]	State	Publication	Recorder species	Sample size	Chronology years	Fire years	Pre-MFI[b] (years)	Post-MFI (years)	Mod. MFI (years)	Season of burn[c]
MW	MO	Stambaugh et al. 2005	Shortleaf pine	23	1634-1974	97	22.4	1.7	70.0	DS
MW	OK	Stambaugh et al. 2013	Shortleaf pine	49	1633-1992	88	5.0	1.7	17.0	DS
MW	TN	Guyette and Stambaugh 2005	Post oak	186	1631-2002	139	8.6	1.2	3.8	n.d.
MW	TN	Guyette et al. 2009	Shortleaf pine	28	1790-2005	32	6.0	4.5	55.0	DS
MW	TX	Stambaugh et al. 2011	Post oak	49	1681-2007	30	6.6	6.3	75.0	DS
NE	PA	Brose et al. 2013a	Red pine	93	1530-2010	55	14.3	3.2	100.0	DS
NE	PA	Lutz 1930	White pine	?	1725-1925	6	37.6	19.5	75.0	n.d.
NE	VT	Engstrom and Mann 1991	Red pine	20	1815-1987	17	?	5.1	90.0	n.d.
NE	VT	Mann et al. 1994	Red pine	32	1504-1851	18	23.1	12.3	100.0	GS

[a]AP = Appalachian Mountains, GL = Great Lakes, MW = Midwest, NE = Northeast.
[b]MFI=Mean fire interval: pre-MFI=before European settlement; post-MFI=after European settlement; mod. MFI= modern times since the beginning of forest fire control policies.
[c]Season of burn: DS = Dormant Season; GS = Growing Season; n.d. = not determined.
[d]? = unknown.

Table 3.—Summary characteristics of the fire scar studies by region

Region	Sample size	Chronology years	Fire years	Pre-MFI[a] (years)	Post-MFI (years)	Modern MFI (years)	Season of burn[b]
All Regions	49	1689-1965	53	13.1	7	46	DS, 75%
Appalachian Mountains	52	1741-1991	61	5.8	5.3	32.4	DS, 88%
Great Lakes	50	1653-1927	36	18.6	11.4	57.8	GS, 50%
Midwest	49	1698-1986	67	8.7	4.4	33.6	DS, 90%
Northeast	48	1644-1943	24	25.0	10.0	91.3	DS, 62%

[a] MFI=mean fire interval in years: pre-MFI= before European settlement; post-MFI=after European settlement; modern MFI= since the beginning of forest fire control policies.
[b]DS = Dormant Season; GS = Growing Season. Percent indicates the proportion of the fires that occurred in that season of burn.

The number and timing of the fire studies varied by region. The Midwest had the most fire history studies (19), and these occurred between 1985 and 2013 (Tables 2 and 3). The Great Lakes was next with 16 studies conducted between 1973 and 2009. The Appalachian Mountains region had 12 studies that took place between 2001 and 2011. The Northeast had only four fire scar studies, but one was the earliest (Lutz 1930) and another was the most recent (Brose et al. 2013a). Mean sample size per study was nearly identical among the four regions (48 to 52 trees per study). The Great Lakes, Midwest, and Northeast had longer chronologies (275 to 300 years) than the Appalachian Mountains chronology (251 years). This is likely due to differences in the longevity and decay rates of the fire-scarred species. The mean number of fire years in a chronology was greatest in the Midwest and Appalachians (67 and 61 fires, respectively) than in the Great Lakes (36) and the Northeast (24), suggesting a climatic influence. Presettlement MFIs were the shortest in the Appalachians (5.8 years), but this may be somewhat skewed by a lack of sample size (7) and particularly short MFIs (2.7 and 3.2 years) in northern Alabama. Other Appalachian studies produced an average MFI of 7 years. The Midwest had a mean presettlement MFI of 8.7 years, and MFIs for the Great Lakes and the Northeast were 18.6 and 25.0 years, respectively. Generally, transitioning into the postsettlement era decreased MFI by about 50 percent. In the Great Lakes, MFI dropped from 18.6 to 11.4 years. In the Midwest, the decrease was from 8.7 years (presettlement) to 4.4 (postsettlement). The Northeast had the largest drop in MFI, from 25.0 to 10.0 years. The Appalachian Mountains region showed no change in MFI. It was 5.8 years before European settlement and 5.3 years afterwards. All four regions showed large increases (6- to 9-fold) in MFI after fire exclusion began. In the Appalachian Mountains and the Midwest, dormant season fires were the overwhelmingly dominant type, but growing season fires composed half of the fires in the Great Lakes and nearly 40 percent of the fires in the Northeast. These seasonal tendencies did not change through time.

Synthesis

The charcoal and fire scar studies collectively revealed the following findings and trends that are informative and useful to forestry managers and researchers:

- **Fire has been a part of upland ecosystems throughout eastern North America since the end of the last ice age.** Paleoecology studies in the Appalachian Mountains, Great Lakes, and Northeast found charcoal dating to at least 5,000 to 10,000 YBP. Fires became more common as Native American populations increased about 4,000 YBP and again as their cultures developed agriculture about 1,000 YBP. The studies revealed a gradient of decreasing fire from south to north and west to east, most likely reflecting climatic changes from warm and/or dry to cool and/or moist.
- **Presettlement (1500 to ~1800 A.D.) fires occurred throughout the eastern oak biome.** We found studies providing pre-1800 data in 18 states and 1 province. Additionally, we found references to presettlement fire scars in four other states. Those studies and references occurred from Texas to Minnesota and Vermont to Alabama.
- **Frequency of presettlement fires varied considerably among and within the four regions of the eastern oak biome.** Fire frequencies ranged from annual fires in the Midwest to century-long fire-free periods in the Great Lakes and Northeast regions. This tremendous variability suggests that lightning was not always the primary ignition source, otherwise fire occurrence would have been less variable. Variability

in fire frequency was likely the result of the many American Indian tribes having different cultural relationships to fire as well as social upheaval as the tribes came into presettlement contact with European influences beginning in the 1500s. The introduction of exotic diseases, life-easing inventions (flint and steel), and intertribal conflicts over the demand for pelts and skins disrupted American Indian societies and led to highly variable fire frequencies. The multi-decadal fire-free periods support the contention of Russell (1983) that fires only occurred where and when there were American Indian tribes. In the absence of American Indian activity, fire was a rare occurrence, especially where climate and topography limited fire spread.

- **A gradient of decreasing presettlement fire frequency existed from south to north.** Pre-1800 MFIs ranged from 2 to 3 years in Alabama to 30 to 40 years in Michigan and Pennsylvania. This gradation likely reflects a climatic influence. There are simply fewer periods of time conducive to fire ignition and spread as latitude increases. A less obvious gradient occurred from west to east. Generally, MFIs were shorter in the central states (Illinois, Missouri, and Oklahoma) than they were in the Appalachian states (Maryland and Tennessee), although there were some notable exceptions such as Virginia. This gradation likely also reflects climate since droughts are more common and severe in the Midwest (Cook et al. 2007), as well as differences in fine fuels (grasses versus leaf litter). Both gradients are confirmed by the fire frequency model developed by Guyette et al. (2012).
- **Presettlement fires generally occurred during the dormant season.** Of the 33 studies that reported fire seasonality, 26 (78.8 percent) found that the pre-1800 fires burned during the dormant season. These dormant season fires may have occurred during the autumn for hunting and nut gathering purposes or during the spring to control pests and snakes or renew berries and grasses. When growing season fires did occur, the scar was situated in the earlywood, suggesting that a dry spring may have extended the spring fire season into the early summer. The predominance of dormant season fires also indicated that American Indians started these fires because lightning is generally restricted to the summer months.
- **Growing season fires were common in the Great Lakes region and the Northeast.** In these areas, growing season fires typically composed about half or more of the presettlement fires. This likely reflects the abundance of pines and lightning as an ignition source (Ruffner and Abrams 1998). Growing season fires may have been historically important in the xeric pine-oak-heath forests of the Appalachians. Recent research at Great Smoky Mountains National Park on unsuppressed lightning fires (Cohen et al. 2007) shows that this forest type can ignite from lightning strikes and the resultant fires can burn for weeks despite precipitation, eventually covering hundreds of acres.
- **Infrequent prolonged (10 to 40 years or more) fire-free periods are critical to permitting oak reproduction to grow into the overstory and are a prerequisite to sustaining upland oak forests.** A single extended fire-free period every century or two is probably sufficient to sustain the overstory for long-lived (200 to 400 years) species. These fire-free periods were common before European settlement (Brose et al. 2013a, Guyette et al. 2003). Long fire-free periods in a regime characterized by periodic fire favored oak and pine regeneration and set the stage for successful recruitment and overstory dominance.

- **Mean fire intervals follow distinct temporal trends.** Most of the studies (73 percent) showed three distinct fire regimes in terms of MFIs. Collectively, these studies had a presettlement MFI of 12.9 years. During European settlement, the overall MFI dropped to 6.3 years. Since the advent of fire exclusion policies in the early 1900s, the overall MFI has risen to 45.2 years. Most of the studies that did not show this temporal trend were in the Appalachian Mountains.
- **More paleoecology studies are needed.** We found no paleoecology studies in the literature for the Midwest and several from the Appalachians were lacking complete analysis.
- **The most suitable species for fire scar research are the hard pines (longleaf, pitch, red, shortleaf, and Table Mountain) and the white oak group (bur, chestnut, post, and white).** This is likely due to their longevity and ability to compartmentalize wounds. The red oak group (black, northern red, and scarlet), other long-lived conifers such as eastern white pine and eastern hemlock, and mesophytic hardwoods are of lesser value because they are more prone to rot after wounding. The functional time span of these species maintaining fire scars seems to be about 500 years as only 2 of the 51 studies had samples dating to 1500 or earlier.
- **High-quality fire history studies are lacking for the Northeast region and the southern Appalachian Mountains.** Prior to this project, only three fire scar studies existed in the Northeast, and one of those suffered from some sampling and methodological shortcomings. In the southern Appalachian Mountains, we found only two, but one study was so insufficient in providing data that we could not include it in this synthesis. Fortunately, there are several active fire scar studies underway in this region that will help elucidate the fire history over the past several centuries.

CHAPTER 3: ADAPTATIONS OF OAK TO FIRE

The second part of the fire-oak hypothesis states that oaks[1] have adaptations that give them a competitive advantage over most other tree species in a periodic fire environment (Abrams 1992, Arthur et al. 2012, Brose et al. 2001, Nowacki and Abrams 2008). This chapter reviews some of the basic fire and silvics literature to provide an overview of the adaptations that give oaks some direct resistance to fire damage during certain life stages. Additionally, this chapter explains how oaks indirectly benefit from a regime of periodic fire due to changes in the environment and competitive relationships during regeneration and recruitment.

The death of vascular tissue in plants occurs when it is subjected to ≥140 °F for 60 seconds or longer (Hare 1965, Wade and Lundsford 1990, Wright and Bailey 1982). However, longer exposure to lower temperatures may also cause the death of tissue. Average maximum temperatures from 174 to 700 °F have been recorded at or near the ground during prescribed fires in hardwood forests in the Missouri Ozarks (Dey and Hartman 2005), Ohio (Hutchinson et al. 2005a, Iverson et al. 2004, Phillips et al. 2007, Rebbeck et al. 2004), and the southern Appalachian Mountains (Elliott and Vose 2005, Greenberg et al. 2012, Phillips et al. 2007). These temperatures are capable of causing death to hardwood stems depending on duration of exposure and tree characteristics. Fire severity with respect to stem damage and mortality is influenced by season, weather, fire type, fire frequency, and factors that affect fire intensity such as fuel characteristics (Bond and van Wilgen 1996, Regelbrugge and Smith 1994, Tester 1996, Van Wagner 1973). The mortality of seeds and stems following fire is also dependent upon the species, location of seed, size of stem, bark thickness, physiological activity, and life stage (Brose and Van Lear 2004).

Acorns

Fire effects on acorns can either positively or negatively impact oak regeneration. Fires that precede an acorn crop by a few months to a year can promote oak seedling establishment (Arthur et al. 2012, Brose et al. 2013b, Wang et al. 2005). Possible mechanisms for this promotion include:

- Reducing the density and size structure of competing species in the mid and understories, thereby increasing light and other resources in the regeneration zone.
- Destroying seed of competitors that is stored in the litter.
- Reducing the thickness of litter to below 2 inches, thereby eliminating any physical barriers to seedling establishment.
- Reducing habitat for insects, fungi, and small mammals that feed on acorns.

Conversely, fires that occur shortly after acorn drop cause substantial seed damage and death (Fig. 13). Auchmoody and Smith (1993) observed that a low intensity fire killed nearly half of the northern red oak acorns in the litter. Greenberg et al. (2012) reported that after a low intensity fire, white oak and northern red oak acorns in the litter that were subjected to 400 °F had high rates of mortality, and all acorns perished when temperatures were above 500 °F. Additionally, surviving acorns often produce low-vigor seedlings (Auchmoody and Smith 1993, Dey and Fan 2009).

[1]Scientific names of the flora and fauna are listed in the Appendix.

Figure 13.—Acorns are one of the life stages of oak that are especially vulnerable to fire. Photo by Daniel Dey, U.S. Forest Service.

Acorns located under matted, wet, and frozen litter are protected from the heat of winter fires. Acorns buried in mineral soil have even greater protection from fire damage because soil is a poor heat conductor when soil moisture contents are at or below field capacity. For example, in low intensity prescribed burns where maximum temperatures reached 325 to 600 °F just above the ground, average soil temperatures were less than 51°F (Iverson and Hutchinson 2002, Iverson et al. 2004). These temperatures did not cause death to buried acorns or roots in the soil. Greenberg et al. (2012) found that after a low-intensity dormant season fire, germination rates for white oak and northern red oak acorns were lower for seed located on the litter surface compared to those in the duff-mineral soil interface or buried in 2 inches of mineral soil.

Seedlings

The location of the acorn at the time of germination is critical for determining whether an oak seedling develops resistance to fire. Acorns have hypogeal germination (Burns and Honkala 1990). The cotyledons remain in the acorn and this is where the root collar and numerous dormant buds form. If the acorn is buried in soil by wildlife, then the root collar and the accompanying buds are insulated from the damaging heat of a fire (Fig. 14). Many of oak's competitors, such as red maple, do not have their seeds buried by wildlife plus they have epigeal germination, i.e., the cotyledons rise up above the ground to become photosynthesizing structures and thus are vulnerable to fire (Fig. 15). This difference in mode of germination and location of the cotyledons and bud bank confers an advantage to oak when fires occur.

Figure 14.—An oak seedling sprout with a well-developed taproot. Note the numerous large dormant buds just below the root collar. These buds help give oak reproduction their tenacious sprouting ability. Photo by Daniel Dey, U.S. Forest Service.

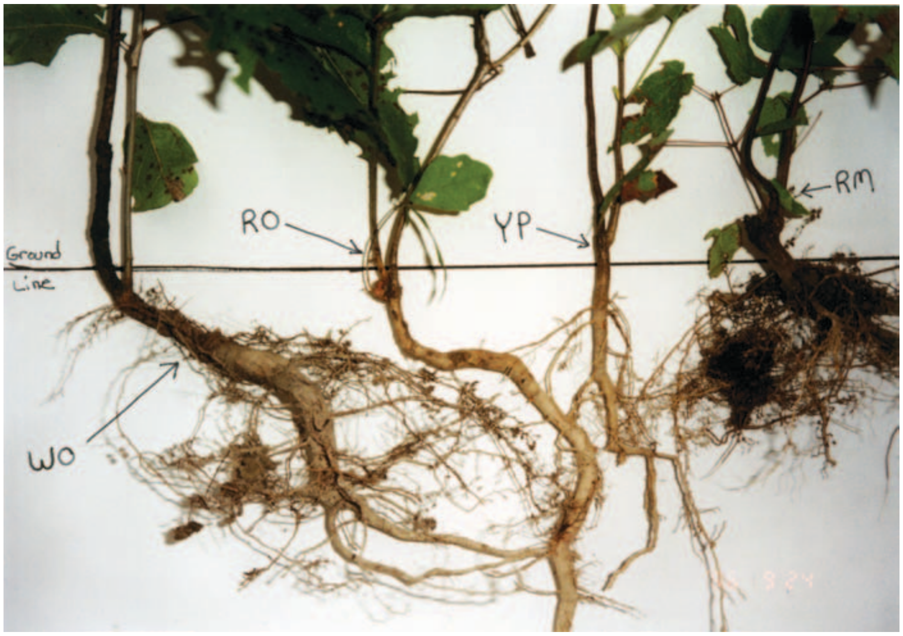

Figure 15.—Origin of sprouts of white oak (WO), red oak (RO), yellow-poplar (YP), and red maple (RM). Note that the RM and YP sprouts originated above ground while those of the oaks originated below ground. Photo by Patrick Brose, U.S. Forest Service.

An important physiological trait of oak seedlings that contributes to its survival and persistence in a fire environment is that they preferentially store carbohydrates in their root tissue (Fig. 16) (Brose 2008, 2011a; Dillaway et al. 2007; Gottschalk 1985, 1987, 1994; Johnson et al. 2009; Kolb et al. 1990; Rebbeck et al. 2011). Root carbohydrate level is important for oak seedling survival in a periodic fire environment because it supports the growth of sprouts following a fire that kills the parent stem. For oak seedlings arising from acorns buried below the duff or in soil, the combination of an abundance of dormant buds and a reserve of carbohydrates stored in root tissue that is protected by soil makes them superior sprouters to most of their hardwood competitors in a periodic fire environment.

Figure 16.—Oak seedlings preferentially develop their root systems more than their stems. This trait helps them survive periodic fires and exploit the post-fire environment. Photo by Patrick Brose, U.S. Forest Service.

Low- to moderate-intensity surface fires topkill most hardwood reproduction, including the oaks (Ferguson 1961, Lotti et al. 1960, McCarthy and Simms 1935, Paulsell 1957, Waldrop et al. 1992). The ability of oak seedlings to sprout postfire increases exponentially as basal diameter increases (Dey and Hartman 2005). Young (e.g., <3 years old) and small (e.g., <0.25-inch basal diameter) oak seedlings are susceptible to mortality by fire because of their thin bark and relatively low root carbohydrate reserves in their small root systems (Johnson 1974, Johnson et al. 2009). Larger diameter oak seedlings have larger root systems and hence greater sprouting capacity (Canadell and Rhoda 1991, Dey and Parker 1997a, Johnson et al. 2009).

Figure 17.—Dense understory shade (top) decreases root development of oak seedlings, but diffuse shade (bottom) is generally sufficient to promote development of large oak advanced regeneration. Photos by Patrick Brose and Daniel Yaussy, U.S. Forest Service.

The key to developing oak reproduction with large root systems is having an adequate amount of sunlight in the forest understory (Fig. 17). Sunlight in undisturbed oak stands is often <5 percent of full sunlight on mesic and hydric sites, which is below the light compensation point for many oak species, and hence is insufficient for net production of biomass (Dey et al. 2008a, 2008b; Johnson et al. 2009). On these sites, midstory canopies dominated by shade tolerant species can develop into overstocked stands, further reducing light levels below that needed for oak persistence and dominance. Also, in northern hardwood forests containing maple and beech, crown density, depth, and volume is greater because of the shade tolerant species compared to pine or oak forests, and this contributes to lower levels of available light in forest understories. Removal of the midstory canopy or reducing overstory density is generally recommended to provide adequate light for oak root development in forests on better quality sites, and the increase in sunlight usually lasts for several years (Brose 2008, 2011a; Brose et al. 2008; Lorimer et al. 1994; Motsinger et al. 2010; Parrott et al. 2012).

Understory light levels on xeric sites are more favorable to promoting oak survival, growth, and accumulation of large advance reproduction (Johnson et al. 2009), even without silvicultural intervention. Sander (1979) reported and Blizzard et al. (2013) measured average light levels of 20 to 25 percent of full sunlight in Missouri Ozark upland oak ecosystems. These forests are relatively more xeric than other eastern deciduous forests and lack strong competitors such as yellow-poplar that are so prevalent in other ecoregions in the eastern United States. The superior drought tolerance and modest nutrient demands of oaks compared to other hardwood species also facilitates the accumulation of oak advance reproduction on the more fire-prone, xeric sites (Johnson et al. 2009).

Saplings

In general, trees gain resistance to fire damage as they grow larger because increased bark thickness improves protection of the cambium. In addition, continued height growth places the crown further from the ground, and therefore, the heat generated by surface fires. Bark thickness is a major determinant of fire resistance regardless of tree species because bark can insulate the cambium and dormant buds from the heat of a fire (Bond and van Wilgen 1996, DeBano et al. 1998, Dickmann 1993, Harmon 1984, Hengst and Dawson 1994). Small differences in bark thickness produce large differences in fire resistance because the duration of heat required to kill tree cambium is proportional to the square of the bark thickness (Hare 1965). Tree stem diameter has been correlated to survival after burning because it is directly related to bark thickness and tree height, and hence to a tree's ability to resist heat injury to the cambium or crown (Dey and Hartman 2005, Hare 1965, Loomis 1973, Regelbrugge and Smith 1994).

Low- to moderate-intensity fires are effective for eliminating saplings when stem diameters at breast height (d.b.h.) are ≤4 inches. (Brose et al. 2013b, Dey and Hartman 2005, Hutchinson et al. 2005b). Trees larger than this d.b.h. are seldom topkilled by most prescribed fires, even if they are fire sensitive species, because their bark is thick enough to give them resistance to stem girdling of the cambium by fire (Fig. 18). Single low-intensity fires often only reduce stand basal area by 5 percent (Dey and Fan 2009, Hutchinson et al. 2005b). A single fire usually

Figure 18.—Single low-intensity fires after an extended absence of fire will probably have little impact on the sapling layer. More intense fires or repeat fires are needed to reduce the sapling layer and decrease understory shade. Photo by Patrick Brose, U.S. Forest Service.

Figure 19.—The ability of a tree to withstand a surface fire is determined by bark properties and fire characteristics which are influenced by a wide variety of biotic and environmental factors. Photo by Patrick Brose, U.S. Forest Service.

decreases the density of small saplings (≤3-inch d.b.h.) by causing stem dieback and formation of sprout clumps (Henning and Dickmann 1996, Paulsell 1957, Thor and Nichols 1973, Van Lear and Waldrop 1991, Waldrop et al. 1992). Repeated low-intensity burning or a single hot growing season fire can increase the amount of basal area reduction (Brose et al. 2013b, Fan et al. 2012, Hutchinson et al. 2005b). Furthermore, sprouts from former saplings are more susceptible to shoot dieback or mortality from additional fires because the stems are smaller in diameter. Thus, periodic fires maintain reproduction as seedling sprouts or stump sprouts, making them unable to increase their fire resistance by growing larger and developing thicker bark. In the process of periodic burning, oak reproduction is favored (Brose et al. 2013b). Dey and Hartman (2005) and Fan et al. (2012) observed differences among species under frequent to annual burns for a decade and reported that oaks and hickories were superior in persistence compared to most of their competitors.

The time since the last fire is a critical variable affecting the response of hardwood saplings to periodic fire. A single low-intensity fire after an extended fire-free period (e.g., >20 years) often causes little damage to oak's competitors because they have grown large enough in diameter and in bark thickness to be fairly fire resistant (Hutchinson et al. 2005b, Waldrop et al. 2008). Harmon (1984) estimated that red maple could grow large enough and have thick enough bark in 23 years to have a 50 percent chance of surviving a low intensity fire.

Mature Trees

Tree species vary in their ability, as mature individuals, to resist wounding by fire (Fig. 19). Several bark properties such as thermal conductivity, specific heat, and thermal diffusivity are important in determining its ability to protect the cambium from the heat of fire, and these properties vary by species (Hare 1965, Harmon 1984). The most widely recognized bark characteristic related to a tree's resistance to fire injury is bark thickness. Pines are the most fire resistance species group largely because of their bark characteristics (Hare 1965, Harmon 1984). Among the hardwoods, large (≥20-inch d.b.h.) oaks are generally considered less susceptible to fire injury and mortality than most of their competitors because their bark is thicker for a given tree size (Harmon 1984, Lorimer 1985). Diameter growth rates are also important because bark thickness is primarily dependent on bole diameter. Growth rates vary among species, degree of dominance or crown class, and site quality.

Species in the white oak group have thicker bark for given diameters than most other hardwoods in the Central Hardwood Region, and they are followed by species in the red oak group (Sutherland and Smith 2000). Thinner barked species include American beech, flowering

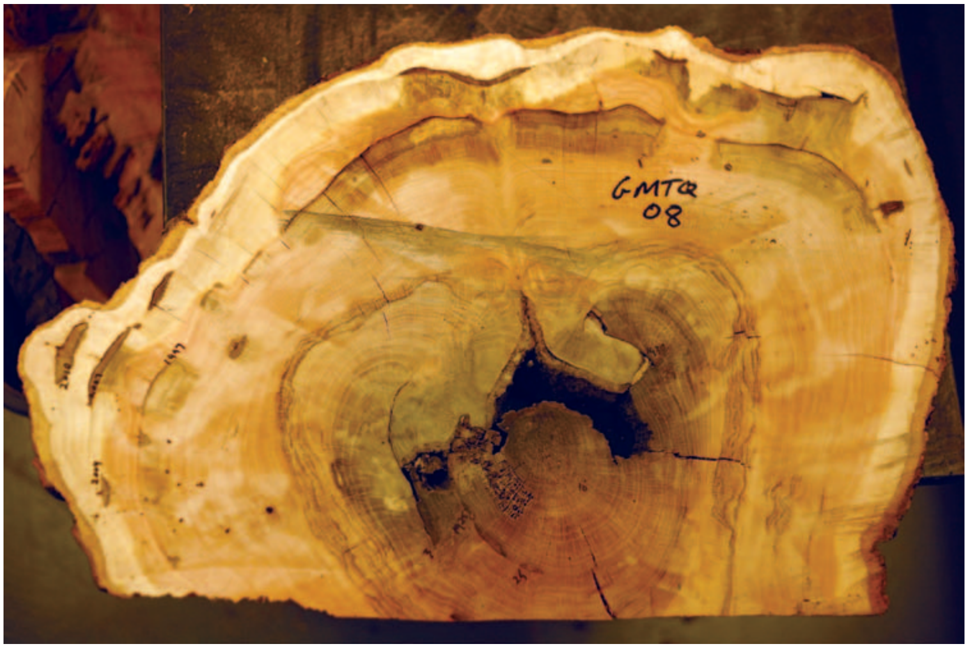

Figure 20.—A cross section of a mature oak from the Missouri Ozarks. Note the numerous healed fire scars. This tree has survived many fires through the decades. Photo by Joseph Marschall, University of Missouri.

dogwood, maples, hickories, and black cherry. Yellow-poplar has thin bark when it is young, but it grows rapidly and bark thickness increases such that it is highly resistant to fire injury as a large diameter tree (Nelson et al. 1933, Spalt and Reifsnyder 1962, Sutherland and Smith 2000). Similarly, eastern cottonwood is thin barked and susceptible as a young tree, but it grows rapidly and produces thick bark to become one of the most heat resistant species (Hengst and Dawson 1994). In contrast, silver maple always has thin bark whether it is small or large in diameter (Sutherland and Smith 2000). Large chestnut oaks are highly fire resistant and are more likely to survive a high intensity fire than pignut hickory or red maple (Regelbrugge and Smith 1994). However, there is substantial variability among the oak species; bur oak is one of the most fire resistant in contrast to scarlet oak (Johnson et al. 2009). Protected from fire by their bark, oaks are able to live closer to their inherent maximum longevity. Species from the white oak group generally live longer than species from the red oak group. For example, post oak can live >400 years, whereas scarlet oak seldom exceeds 150 years old. Once oaks make it into the overstory as codominant or dominant trees, they can persist for a long time.

Mature overstory trees are also taller, so their crowns are further from the ground making them less susceptible to damage from surface fires. A higher intensity fire is needed to kill larger (>10-inch d.b.h.) overstory trees (Hutchinson et al. 2005b). However, trying to control overstory density with more intense fires is less precise than harvesting trees using the shelterwood method, which gives better control over the trees that are removed and the location of canopy gaps.

When trees are scarred by fires, they have a suite of defenses that enable them to contain the injury and minimize the detrimental effects which include wood decay, loss of structural strength with advanced decay, and shortened lives. When oaks are scarred by fires they are capable of rapidly and effectively compartmentalizing wounds (Fig. 20) (Smith and Sutherland

1999). This limits the spread of decay throughout the stem and increases a tree's longevity in the overstory where it may potentially be a seed producer for decades. Species in the white oak group (bur oak, chestnut oak, post oak, and white oak) are effective at compartmentalizing decay (Sutherland and Smith 2000) and are considered resistant to very resistant to decay. In contrast, species in the red oak group, hickories, maples, and yellow-poplar are considered only slightly resistant or nonresistant (Berry 1969, Nelson et al. 1933, Spalt and Reifsnyder 1962, U.S. Forest Service 1967). Therefore, large diameter red oak trees are resistant to being wounded by low intensity surface fires, but if they receive a large enough wound to permit fungal infection, they decay relatively quickly. Trees with decay in their boles are more subject to breakage or blowdown in high winds or under the weight of heavy ice and snow loads. Wood decay resulting from fire wounds reduces the longevity of the oaks in the overstory by increasing the likelihood that they will succumb to stem breakage, blowdown, or death due to impaired physiological functioning.

Synthesis

Oaks have a suite of attributes that give them a survival advantage in a periodic fire regime and the means to exploit the postfire environment, but their response to fire varies at different stages of their life cycle. Some common characteristics of oaks are listed below:

- **The hypogeal germination trait of acorns results in the root collar and the accompanying basal buds forming at or beneath the soil surface.** This trait protects the root collar and buds from the lethal temperatures of a fire. This protection is further enhanced if the acorn had been buried by wildlife, which is usually the case.
- **Oak seedlings emphasize root development in lieu of stem growth.** Provided there is sufficient light, oak seedlings quickly build large root systems relative to their stems. This trait bestows superior survival to oak seedlings relative to their mesophytic competitors that emphasize stem height growth more than root development. Once the root collar diameter is >0.25 inch, the oak seedling will likely sprout from a basal bud if it is topkilled by a fire (Brose and Van Lear 2004). Once the root collar diameter is >0.75 inch, the seedling is capable of relatively rapid, sustained height growth provided there is sufficient sunlight (Brose 2011a, Brose et al. 2008). The emphasis on root development allows oak reproduction to withstand periodic surface fires and exploit the postfire environment. Root development also bestows superior survival to oaks on dry sites, nutrient poor sites, and during droughts relative to the mesophytic hardwoods.
- **As oaks mature, they develop thicker, more fire resistant bark relative to many of the mesophytic hardwood species.** Bark has several characteristics that convey protection from fire. Thickness and texture are two of them. For trees of an equal size, oaks will usually have thicker bark than most of the mesophytic hardwood species. Additionally, oaks tend to have flaky and/or corky-textured bark that is more resistant to heat penetration than solid bark. Among the oaks, those species in the white oak group have superior bark for thwarting conductive heat transference than those species in the red oak group.

- **When oaks are injured by fire, they are better at compartmentalizing wounds than most of the mesophytic hardwood species.** Because oaks have ring porous radial growth and complex cell chemistry (tyloses), they can quickly isolate injuries and prevent decay from spreading throughout their boles. This is especially true for species of the white oak group. Consequently, oaks can survive injuries longer than many of the mesophytic hardwood species, resulting in increasing oak dominance through time.
- **There are two stages in the oak life cycle that are vulnerable to fire.** Fires at the time of or shortly after acorn drop are detrimental to oak regeneration because of high acorn mortality. Similarly, young oak seedlings are susceptible to mortality, especially from growing-season fires, because they have not yet developed large root systems.

CHAPTER 4: REVIEW OF FIRE EFFECTS STUDIES

The fourth part of the fire-oak hypothesis asserts that prescribed fire can help regenerate oak ecosystems in some situations. To test this assertion, we collected 58 papers produced by 43 prescribed fire projects conducted in 14 states (Fig. 21) and examined their findings for trends. The projects were sorted by stand type (mature, young, or immature), season of burn (dormant or growing), and number of fires (single [1], dual [2], or multiple [>2]) based on the site descriptions and methods provided in the publications. Stands were considered mature if they had a fully stocked overstory, a ubiquitous midstory, and the oak[1] seedlings were either lacking or quite small. Generally, these stands had been undisturbed for years or had only recently been disturbed by light, thin-from-below treatments. In terms of stand dynamics, mature stands were beginning the understory re-initiation stage of development (Oliver and Larson 1990) and the oak regeneration process. Young stands included those that were undergoing a shelterwood harvest sequence and those that had recently received a final harvest. Oak and mesophytic hardwood reproduction was abundant and vigorous, and these stands were near or at the end of the oak regeneration process. Also, the time between the harvest and the fire was at least three growing seasons. Immature stands were intermediate between young and mature stands. Their canopies had recently closed, but they were several decades from being mature. Structurally, there were hundreds to thousands of small-diameter trees (3- to 10-inch diameter at breast height [d.b.h.]) per acre that were undergoing density-dependent mortality. Immature stands were in the stem exclusion stage of stand development (Oliver and Larson 1990).

[1]Scientific names of the flora and fauna are listed in the Appendix.

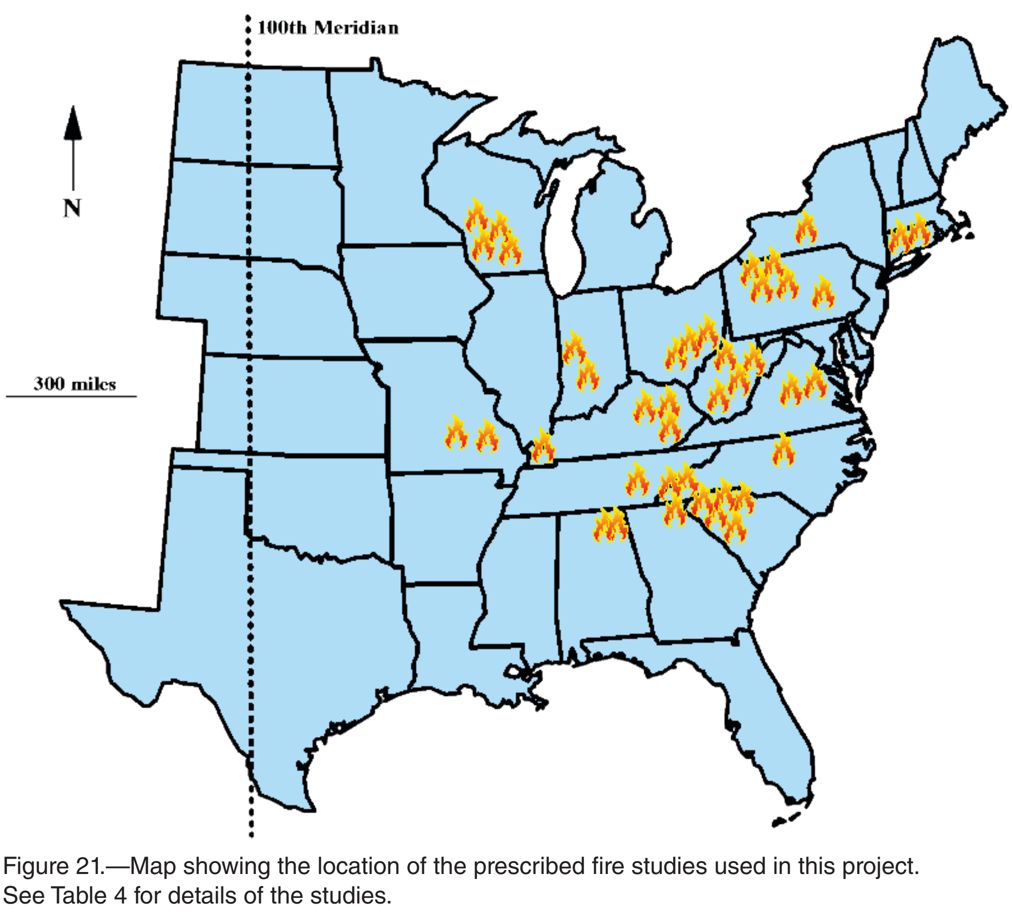

Figure 21.—Map showing the location of the prescribed fire studies used in this project. See Table 4 for details of the studies.

Dormant season fires occur between leaf abscission in autumn and leaf expansion the following spring. During this time, the hardwood reproduction is not photosynthesizing, although sap flow may occur in the early spring before leaf expansion begins. Growing season fires take place between leaf expansion in the spring and leaf abscission in autumn. The exact starting time of the growing season is highly variable and is governed by location, weather, and the physiological characteristics of the hardwood species. For example, leaf expansion in mesophytic hardwood reproduction usually begins several days to a few weeks before it begins in oak reproduction. Therefore, one species group is photosynthesizing while the other is still dormant. We considered the beginning of the growing season to be when the leaves of the mesophytic hardwood reproduction were ≥50 percent expanded.

After sorting the projects by stand type, season of burn, and number of prescribed fires, we examined the results in each paper to determine whether the fire treatment effects on oak reproduction were positive, negative, or ambiguous. Positive effects on oak reproduction included absolute increases in oak seedling density via establishment of new germinants, relative increases to the oak portion of the regeneration pool via differential survival rates between oak and mesophytic hardwoods, or acceleration of postfire oak seedling height growth relative to that of other species. Negative fire effects on the oak reproduction included decreases in the absolute or relative abundance of oak reproduction or loss of the relative oak seedling height growth. Ambiguous results were when there was little or no meaningful change in competitive relationships between oak and mesophytic hardwood reproduction from preburn to postburn.

Mature Stands

Of the 43 fire projects, 31 (72 percent) took place in mature stands and 29 (93 percent) of those involved dormant season fires (Table 4). These were relatively evenly spread among the number of fires (11 single-burn, 12 dual-burns, and 8 multiple-burns) and among effects on oak (9 ambiguous, 11 negative, 11 positive). However, when these two groupings (number of fires and effects on oak) were combined, a pattern of improving benefit to oak as the number of fires increased was evident (Table 5). The balance of the first portion of this chapter will review some of the noteworthy publications that are representative of the studies conducted in mature stands.

Dormant Season Fire

Single Fire

The effect of a single prescribed fire on existing oak seedlings was either negative or ambiguous (Tables 4 and 5). Of the 11 studies, 7 found that the number of oak seedlings decreased following the fire while the other 4 found no substantial change. Of these, the Johnson (1974) study is fairly typical in terms of study design, implementation and outcome.

Johnson's study took place in southwestern Wisconsin and involved the U.S. Forest Service North Central Forest Experiment Station and the Wisconsin Department of Natural Resources. The study site was an 8-acre stand dominated by northern red oak. The stand was moderately thinned from below (basal area reduced from 120 to 80 square feet per acre) in autumn 1969. At this same time, an acorn crop resulted in the establishment of 7,000 new red oak seedlings per acre in spring 1970. A year later the stand was split in two, and one section was burned with

Table 4.—Prescribed fire papers reviewed for assessing fire effects on hardwood reproduction organized by stand type, season of burn, and number of burns

State	Location[a]	Publications[b]	Stand type[c]	Season of burn[d]	Number of burns	Effects on oak[e]
AL	Bankhead NF	Huntley and McGee 1983	M	D	1	N
GA	Chattahoochee NF	Loftis 1990	M	D	1	N
IN	Purdue Forest	Dolan and Parker 2004	M	D	1	A
NC	Nantahala NF	Elliott et al. 2004	M	D	1	A
OH	Vinton Furnace EF	Albrecht and McCarthy 2006	M	D	1	A
SC	Sumter NF	Teuke and Van Lear 1982	M	D	1	A
WI	Hardies Creek SF	Johnson 1974	M	D	1	N
WV	Geo. Wash. NF	Wendel and Smith 1986	M	D	1	N
WV	Westvaco Forest	Collins and Carson 2003	M	D	1	N
PA	Clear Creek SF	Brose et al. 2007	M	G	1	N
PA	Moshannon SF	Gottschalk et al.[f]	M	G	1	N
IN	Morgan SF	Merritt and Pope 1991	M	D	2	A
KY	Land / Lakes NRA	Franklin et al. 2003	M	D	2	A
KY	Red River Gorge	Arthur et al. 1998	M	D	2	N
NC	Green River WMA	Waldrop et al. 2008	M	D	2	P
NY	Broome County	McGee et al. 1995	M	D	2	A
OH	Zaleski SF	Iverson et al. 2008	M	D	2	P
OH	Zaleski SF	Waldrop et al. 2008	M	D	2	N
SC	Clemson Forest	Barnes and Van Lear 1998	M	D, G	2	P
SC	Clemson Forest	Wang et al. 2005	M	D	2	P
WI	Baxter Hollow	Will-Wolf 1991	M	D	2	A
WV	Fernow EF	Schuler et al. 2013	M	D	2	P
KY	Daniel Boone NF	Alexander et al. 2008	M	D	3	N
KY	Dinsmore Woods	Luken and Shea 2000	M	D	3	N
KY	Red River Gorge	Green et al. 2010 Blankenship and Arthur 2006 Gilbert et al. 2003	M	D	3	A
PA	Ft Indiantown Gap	Signell et al. 2005	M	D	4	P
MO	Chilton Creek Tract	Fan et al. 2012 Dey and Hartman 2005 Sasseen and Muzika 2004	M	D	4	P
OH	Vinton Furnace EF	Hutchinson et al. 2012 Hutchinson et al. 2005a Hutchinson et al. 2005b	M	D	4	P
MO	University Forest	Huddle and Pallardy 1996 Paulsell 1957	M	D	10+	P
TN	University Forest	Stratton 2007 DeSelm et al. 1991 Thor and Nichols 1973	M	D	10+	P
AL	Bankhead NF	Huntley and McGee 1981 Huntley and McGee 1983 McGee 1980	Y	D	1	N
WI	Schmeeckle Reserve	Reich et al. 1990	Y	D	1	A
CT	Goodwin SF	Ward and Brose 2004	Y	G	1	P
PA	State Game Land 29	Brose 2013	Y	G	1	P
SC	Clemson Forest	Geisinger et al. 1989	Y	G	1	A
SC	Clemson Forest	Stottlemyer 2011	Y	G	1	P

continued

Table 4.—continued

State	Location[a]	Publications[b]	Stand Type[c]	Season of burn[d]	Number of burns	Effects on oak[e]
VA	Horsepen WMA	Brose 2010 Brose and Van Lear 1998 Brose and Van Lear 2004 Brose et al. 1999a	Y	D, G	1	P
VA	Powhatan WMA	Keyser et al. 1996	Y	G	1	P
PA	Allegheny NF	Brose[g]	Y	G	2	P
WI	Jordan Timberlands	Kruger and Reich 1997	Y	G	2	P
CT	Cockaponset SF	Ward and Stevens 1989	I	G	1	P
NC	Duke Forest	Maslen 1989	I	D	1	A
WV	WVU Forest	Carvell and Maxey 1969	I	D	1	P

[a]EF = Experimental Forest, NF = National Forest, NRA = National Recreation Area, SF = State Forest, and WMA = Wildlife Management Area.
[b]For studies producing multiple papers, the primary paper is listed first.
[c]M = mature, Y = young, I = immature.
[d]D = dormant season, G = growing season.
[e]A = ambiguous, N = negative, P = positive.
[f]Unpublished data on file at the U.S. Forest Service Lab, Morgantown, WV.
[g]Unpublished data on file at the U.S. Forest Service Lab, Irvine, PA.

Table 5.—Distribution of prescribed fire projects conducted in mature oak forests by the number of burns and the effect on oak regeneration process. Note the trend of increasingly positive effects on oak as the number of fires increase from one to more than two.

	---------------------------Number of Fires----------------------------			
Effect on Oak	Single (1)	Dual (2)	Multiple (>2)	Total
Positive	0	6	5	11
Ambiguous	4	4	1	9
Negative	7	2	2	11
Total	11	12	8	31

a low-intensity prescribed fire while the other served as an unburned control. Data collected that autumn indicated that the burned seedlings had a 40 percent survival rate while the control seedlings had a 90 percent survival rate. The fire had killed approximately half of the northern red oak seedlings.

One of the criticisms of the Johnson (1974) study is that it reports results collected from one inventory conducted just a few months after the fire. A comparable study with a longer interval between treatment and inventory is Wendel and Smith (1986). This study occurred in central West Virginia and was a cooperative effort by the U.S. Forest Service Northeastern Forest Experiment Station, the Washington National Forest, and the West Virginia Department of Natural Resources. Like the Johnson study, this site was thinned to 90 square feet per acre basal area and burned a year later. Prior to the fire, desirable hardwood reproduction was measured at 3,814 stems per acre, and 5 years later the density was 3,500 stems per acre. However, within these numbers, the amount of oak dropped by nearly 80 percent while the amount of red maple and black locust increased by 17 and 120 percent, respectively. Clearly, the fire had set back the oak regeneration process.

Why did these prescribed fires produce such negative results for the oak reproduction? The main problem with both of these studies was that the oak seedlings were small and had been growing in dense understory shade for all of their lives. Consequently, they had small root systems with little root carbohydrate reserves and simply could not sprout postfire. Second, the prescribed fires were conducted in mid- to late-April so the small seedlings may have already begun expanding their leaves, further lowering their root carbohydrate reserves. Finally, neither study excluded white-tail deer from the sites, so excessive deer browsing may have subsequently eliminated many oaks that sprouted postfire. Regardless of why these studies failed to promote oak reproduction, it is evident that prescribed burning can impede the oak regeneration process under some circumstances.

Another impact of single prescribed fires on the oak regeneration process is their effect on recently fallen acorns. This facet of fire and the oak regeneration process was the earliest one reported in the scientific literature. Korstian (1927) found that fires exceeding 400 °F readily killed acorns, but there was a mortality gradient among species with acorns of the red oak group surviving fire at a higher rate than those of the white oak group. Korstian surmised that this gradient was caused by the differences in germination timing (autumn for white oaks, spring for red oaks) between the two groups. Subsequent research has confirmed that acorns are easily killed by fires (Auchmoody and Smith 1993, Dey and Fan 2009, Greenberg et al. 2012).

Dual Fires

Studies utilizing two prescribed fires showed varying responses (Tables 4 and 5). Most reported ambiguous effects (Franklin et al. 2003, McGee et al. 1995, Merritt and Pope 1991) on the oak reproduction with some showing positive outcomes (Barnes and Van Lear 1998, Schuler et al. 2013) and a few showing negative outcomes (Arthur et al. 1998, Luken and Shea 2000). Two oak sites that were part of the National Fire and Fire Surrogate Project illustrate this confusion as they report differing outcomes between sites as well as among topographic positions (Iverson et al. 2008, Waldrop et al. 2008).

The oak sites from the National Fire and Fire Surrogates Project were used to examine the responses of hardwood reproduction and many other variables to prescribed fire and mechanical fuel reduction treatments in western North Carolina and southern Ohio (Waldrop et al. 2008). Dormant season strip-heading fires were conducted twice at both sites with and without a mechanical treatment. In North Carolina, the mechanical treatment was chainsaw felling of shrubs while overstory thinning was the mechanical treatment used in Ohio. Oak regeneration varied by treatment at both sites. In North Carolina, the oaks showed little response to any treatment during the first year but increased significantly in number between years 1 and 3 in the burn only and mechanical plus burn plots. A decrease was observed in year 5 after the second burn, but the difference was not significant. The mechanical-only treatment had little initial impact on oak regeneration in North Carolina, but a significant increase was observed between years 3 and 5. Oak numbers decreased at the Ohio site in all treatment units during the first year, although the difference was not significant in the mechanical-only treatment unit. No changes occurred between years 1 and 4.

Competitors of oak tended to follow the same patterns in North Carolina and Ohio. Red maple showed little response to treatment during the first year in North Carolina, but in Ohio there were significant decreases in the number of red maple seedlings in all treatments, including the control. Burning with and without mechanical treatment significantly increased red maple numbers in year 3 (North Carolina) or year 4 (Ohio), but in North Carolina, the second burn reduced numbers to pretreatment levels. Yellow-poplar increased over time in the mechanical-only plots in Ohio. However, this response was small in comparison to the large increase in numbers of yellow-poplar seedlings observed the first year after burning at both sites. The numbers of yellow-poplar seedlings decreased by the third measurement at both sites and even more after the second burn in North Carolina. This result agrees with the results of Brose and Van Lear (1998) who emphasized the need for prescribed burning after yellow-poplar seedlings become established. Oaks were 4 to 6 times more numerous after the second burn in North Carolina than were seedlings of yellow-poplar. The burn-only treatment changed stand structure by reducing the sapling/shrub layer, but it did little to thin the overstory.

Iverson et al. (2008) used the same study area in Ohio as Waldrop et al. (2008) to compare treatment impacts as they varied across different positions of the landscape. Study plots in Ohio were larger than those in North Carolina (50 acres vs. 20 acres) thus allowing a comparison of treatment impacts across dry and mesic sites. The drier landscape positions generally had more intense fires, more canopy openness, and more oak and hickory advance regeneration; several other tree species also exhibited marked landscape variation in regeneration after treatments. Though advance regeneration of several competing species became abundant after the initial treatments, the second fires reduced the high densities of the two major competitors, red maple and yellow-poplar. The authors suggested that on dry or intermediate sites with at least 2000 oak and hickory seedlings per acre, reducing canopy cover by 8 to19 percent followed by at least two fires should promote oak and hickory to be competitive over about 50 percent of the area. However, no appreciable oak and hickory regeneration developed on mesic sites.

The study by Iverson et al. (2008) on relatively large (>50 acre) treatment units showed some promise as well as some of the problems that managers face. Though thinning and burning increased the density of oak advance regeneration, there also was ample competition from species that had different strategies in dealing with the new conditions brought about by the thinning and burning. Oak regeneration varied spatially across the large sites because topography, fire intensity, and canopy openness were also highly variable. A simple model for this region suggests that if a mature forest on a dry or intermediate site with at least 2000 oak and hickory seedlings per acre is thinned to 80 percent canopy cover and burned to reduce competition and sustain canopy openness, there is a 50 percent chance (or 50 percent of the treated area matching these criteria) of oak and hickory successfully becoming competitive for a position in the next forest.

Multiple Fires

Even though prescribed burning in hardwoods has been discussed for several decades, it was not used on an operational scale until the 1980s (Van Lear and Waldrop 1991). Consequently, long-term studies involving multiple fires in hardwood forests are rare, but a number of new publications are available describing results after three or four periodic fires. Generally, these studies describe positive effects of multiple prescribed fires on oak reproduction, but a few report negative effects (Tables 4 and 5).

One of the longest running fire studies in eastern hardwood forests is located in Tennessee (Stratton 2007). In 1962, an oak barren in south central Tennessee was divided into 3 treatments (burned annually, burned every 5 years, or not burned) and these treatments have been implemented for the past 50 years. Oak has become the dominate species in the understory as mesophytic hardwood reproduction has gradually died out, but none of the oak reproduction has successfully grown into the canopy in any of the fire treatments. Apparently, a 5-year fire return interval is too short for oak reproduction to grow large enough to withstand a surface fire without being topkilled and forced to sprout again.

Blankenship and Arthur (2006) used a study site on the Cumberland Plateau in eastern Kentucky to examine stand structure after prescribed burning two or three times. The same study site was used by Green et al. (2010) after another set of burns (three and four burns) to examine oak and red maple seedling survival. Burning was conducted by backing fire down the ridge and by point source or strip-heading fires if a higher intensity was desired. Fires were in the dormant season for the first two fires and then switched to the growing season for later burns. Burning altered stand structure by reducing overstory stem density by 30 percent and midstory stem density by 91 percent (Blankenship and Arthur 2006). Midstory oak and red maple stem densities were reduced by 94 and 85 percent, respectively. Damaged or dead overstory and midstory stems sprouted, greatly increasing the number of trees in the ground layer, with oak, red maple, and dogwood being the most common species after three burns. Green et al. (2010) tagged chestnut oak, scarlet oak, and red maple seedlings and followed survival and growth through three and four prescribed fires. Burning reduced the numbers of seedlings of all three species, but scarlet oak had significantly higher survival than chestnut oak and red maple. Scarlet oaks that were burned four times were significantly taller than chestnut oak and red maple burned either three or four times. Overall, scarlet oaks had better survival and growth than red maples but were not able to eliminate the maples. Both papers (Blankenship and Arthur 2006, Green et al. 2010) emphasized that after several burns, oak regeneration was in a better competitive position than red maple, but the goal of producing predominately oak regeneration had not been reached. Additional burning and/or implementation of other silvicultural treatments are necessary to reach that goal.

Alexander et al. (2008), also working in Kentucky, had similar results to Blankenship and Arthur (2006) and Green et al. (2010). Numbers of midstory trees were reduced by burning one or three times, but sprouting caused large increases in the numbers of trees in the smaller size classes. Both single and repeated prescribed burns increased understory light and reduced red maple survival. However, neither burning regime placed oaks in an improved competitive position. The authors suggest that successful oak regeneration is difficult to predict because it is controlled by three highly variable and interdependent factors: life history traits of oaks compared to competitors, preburn stature of oak seedlings, and variability of fire characteristics. Although not suggested by these authors, other factors that also control oak regeneration are understory light levels, site quality, and landscape attributes (aspect, slope, and slope position).

Hutchinson et al. (2005a, 2005b) studied regeneration after two and four dormant season prescribed burns on xeric, intermediate, and mesic sites in southern Ohio. Burning, conducted by strip-heading fires, had little impact on overstory trees over 10-inch d.b.h. The density of smaller trees (4- to 10-inch d.b.h.) was reduced by 31 percent after burning twice and by 19 percent after burning four times. The two-burn treatment had higher fire intensity, resulting in greater mortality of small trees. Burning also reduced sapling density by 86 percent.

Regeneration after burning was numerous and included the same species that were killed by burning. In this trial, results were similar among xeric, intermediate, and mesic sites. The largest change was brought about by the higher fire intensities associated with the two-burn scenario which was better at opening the canopy. In addition, burning at longer intervals may have allowed greater buildup of fuels as stems and branches of trees killed by one fire fall over and become fuel for the next fire. Waldrop et al. (2010) found that over time, fine woody fuels increase in abundance after burning until the next prescribed fire. A factor often overlooked is delayed mortality which can occur for several years after a single fire. Yaussy and Waldrop (2010) showed that the likelihood of mortality was related to prior tree health, size class, species, and first-order fire effects. Hutchinson et al. (2012) concluded that periodic fire, coupled with natural gap dynamics, may be a feasible management strategy for perpetuating oak forests where harvesting is not an option.

Growing Season Fire

Single Fire

In our survey of the fire and oak literature, we found only three studies reporting results of a single growing season fire in a mature stand. The Barnes and Van Lear (1998) study occurred on the Clemson University Forest in South Carolina while the Brose et al. (2007) and Gottschalk et al. (2013) studies took place in Pennsylvania on the Clear Creek and Moshannon State Forests, respectively. Barnes and Van Lear (1998) compared a single growing season fire in 1992 to three dormant season fires conducted in 1990, 1992, and 1993. All burns began with backing fires and were completed with strip-heading fires. Postburn oak density was not significantly different between the two burning treatments. The single growing season burn was as effective at promoting open growing conditions as were the three dormant season burns. Additionally, burning in the growing season was more effective at reducing competition from yellow-poplar. This study suggests that even though burning in the growing season is more difficult than in the dormant season, it can be more effective and, ultimately, less expensive.

In the two Pennsylvania studies, postfire sprouting of oak seedlings was 65 percent less than that of mesophytic hardwood reproduction. This large difference between the two species groups was likely due to the oak seedlings having much smaller root systems relative to the larger non-oak reproduction.

Dual and Multiple Fires

None of the mature hardwood studies we reviewed included two or more growing season fires. However, a long-term fire study conducted in pine-dominated stands on the Santee Experimental Forest of South Carolina does provide some insight into this type of fire regime (Langdon 1981, Lewis and Harshbarger 1976, Lotti et al. 1960, McKee 1982). The study was established in 1946 with annual and periodic (every 3 to 5 years) burning conducted in summer and winter until Hurricane Hugo severely damaged the study in September 1989. Waldrop et al. (1992) reported on changes to vegetation through 43 years of treatment. When plots were burned every 3 to 5 years, either in summer or winter, trees >5-inch d.b.h. were largely unaffected as they were too tall and their bark was too thick to be impacted by low-intensity burning. Trees with a d.b.h. between 1 and 5 inches were topkilled gradually over time. These stems then sprouted, resulting in a large increase in stems ≤1-inch d.b.h. Annual winter burning

Table 6.—Distribution of prescribed fire projects conducted in young oak forests by the number of burns and the effect on oak regeneration process. Note the clustering of studies reporting positive effects on oak after just one or two burns.

	Number of Fires			
Effect on Oak	Single (1)	Dual (2)	Multiple (>2)	Total
Positive	6	2	0	7
Ambiguous	2	0	0	2
Negative	1	0	0	1
Total	9	2	0	11

produced similar results, but the largest number of sprouts was in this treatment. With each of these treatments, vegetation had at least one growing season to recover from burning. It was only in the annual summer burn treatment and only after many burns that hardwoods were nearly eliminated from the forest floor. The most resilient species were the oaks which persisted through 18 to 20 annual summer fires (Langdon 1981). This result has been cited by many authors as an indication of the competitive advantage of oaks over other hardwoods in a regime of frequent burning. However, the density of oak competitors increased in all fire regimes except annual summer burning, a fire treatment regime that is impractical for most land managers.

Young Stands

We found 10 prescribed fire projects conducted in young stands (Tables 4 and 6). Unlike the studies in mature stands, only three involved dormant season fires, while eight used growing season burns (note that one project provided data on both seasons-of-burn). Similarly, the fire studies in young stands were not evenly distributed by number of burns and effects on oak reproduction like those conducted in mature stands. Rather, they were concentrated in the single fire and positive effects categories.

Dormant Season Fire

Single Fire

Just three studies reported results of single fires conducted in young stands during the dormant season. Huntley and McGee (1981) burned 3-year-old hardwood clearcuts in northern Alabama. They found that the dormant season fire reduced the density of yellow-poplar reproduction but had virtually no impact on red maple. Density of oak reproduction was also unaffected. In central Virginia, Brose and Van Lear (1998) investigated the impact of a single dormant season burn on hardwood reproduction in oak shelterwood stands. Like the Alabama study, they found decreases in the density of yellow-poplar reproduction, but little reduction of red maple density, except where the fires were intense. A follow-up study (Brose 2010) showed that these initial findings persisted, especially on the more intensely-burned plots, and stands were leading towards eventual oak domination.

Growing Season Fire

Single Fires

Like the dormant season fire studies in young stands, research into the effects of growing season fires is sparse. We found eight studies that had growing season prescribed fires as one of the treatments. In central Virginia, Keyser et al. (1996) found that summer fires in oak shelterwood stands reduced the density of red maple and yellow-poplar seedlings by 82 and 97 percent, respectively, relative to the unburned controls. Oak reproduction decreased by only 11 percent following summer burning. Postfire height growth among the species groups was equal. This small study spawned a more comprehensive research project that was also conducted in central Virginia (Brose and Van Lear 1998, Brose et al. 1999a) and included late spring and summer prescribed fires as treatments in oak shelterwood stands. Results from the previous summer burn were verified. Densities of red maple and yellow-poplar reproduction declined by 46 and 72 percent, respectively, while oak seedling density dropped by only 5 percent. Additionally, late spring burning resulted in a 45 percent decline in stem density for the two non-oak species while oak density actually increased (an artifact of the sampling design). The importance of fire intensity was evident in that the largest reductions in stem densities of maples and yellow-poplars occurred where the fires burned the hottest. This relationship between fire intensity and oak dominance was still present 11 years later (Brose 2010).

Besides burning in oak shelterwoods, growing season fires after the final harvest have been studied to a limited extent. In Connecticut, Ward and Brose (2004) found that mortality of black birch ranged from 66 to 86 percent following mid-spring burning in a recently regenerated mixed hardwood stand. Mortality of red maple averaged 15 percent but varied widely (0 to 100 percent) depending on fire intensity and size of the red maple reproduction prior to the fires. Oak mortality averaged just 9 percent with low variability. In Pennsylvania, Brose (2013) investigated the effects of mid-spring prescribed fires on hardwood reproduction in former oak stands that had recently received the final harvest of a three-cut shelterwood sequence. As in Connecticut, black birch exhibited large decreases in stem densities (~90 percent) while stem density of red maple declined approximately 50 percent. Density of oak reproduction was unchanged by the burning, and virtually all oak stems sprouted after the fires. Similar to oak, the densities of black cherry, cucumbertree, and serviceberry were the same after the fires as before. Besides reducing the stem densities of black birch and red maple, the growing season fire equalized the height growth among the various species.

Immature Stands

Only three publications address fire effects in immature stands (Table 4), and all are reviewed here. In West Virginia, Carvell and Maxey (1969) studied a sapling stand partly burned by an autumn wildfire 5 years earlier. In the unburned portion, yellow-poplar was the dominant species in terms of density and size. However in the burned section, oak and hickory dominated. They noted that 40 to 70 percent of the saplings that survived the fire had large basal scars and concluded that fire was a poor means to manipulate species composition in sapling stands given the loss of future timber value.

Maslen (1989) reported on a single high-intensity dormant season strip-heading fire in a mixed hardwood pole stand in the Piedmont of North Carolina. This study looked at understory characteristics 7 years after burning, giving a slightly longer-term view of fire impacts. By then, there were no significant differences in the numbers of oaks and competitors less than 2 feet tall because seedlings and sprouts had grown into the next larger size class. In the 2- to 12-foot height class, all species including oaks and yellow-poplar were significantly greater in number than prior to burning. Oaks over 12 feet tall at the time of the fire were essentially unaffected by burning and survived the fire. The results of this study indicated that a single prescribed fire did little to the stand other than to remove small regeneration and allow sprouts to grow back over time.

In Connecticut, Ward and Stephens (1989) reported the long-term (55 year) effects of a summer wildfire that burned through part of a 30-year-old mixed hardwood stand in 1932. Prior to the wildfire the stand contained approximately 1,050 stems >1.0-inch d.b.h. per acre and 74 square feet per acre of basal area. Oak and hickory made up 21.3 and 6.4 percent of the stems, respectively, with the balance consisting of birch, maple, and other hardwoods. In the years just after the 1932 fire, stem densities and basal area in the burned area dropped by 84 and 38 percent, respectively, with few differences among species. In the subsequent decades, stem densities in the burned area quickly recovered due to sprouting of the fire-killed stems before declining due to natural stand thinning. At the same time, basal area gradually increased. By 1987, stem densities and basal areas were equivalent in the burned and unburned areas, but the burned area contained considerably more oak (160 stems per acre) than the unburned area (65 stems per acre). Negative effects of the 1932 fire included the widespread bole damage to the trees that survived the fire and the poor stem form of many of the sprouts that developed postfire.

Synthesis

Variations in initial starting conditions, study design, and implementation of the prescribed fire treatments coupled with the low overall sample size limited the use of traditional statistical approaches to analyze the data in Tables 5 and 6. To overcome these methodological challenges, we conducted a meta-analysis of the data from 32 of the 42 prescribed fire projects in Table 4. Complete results of the meta-analysis are available in Brose et al. (2013b) and are summarized below.

In the meta-analysis, we tested five research questions. The first four questions addressed the oak regeneration process while the last one examined stand structure. The five questions were:

1. Does the density of new oak seedlings (germinants) increase postfire?
2. Does oak reproduction basal sprout after prescribed fires at a higher rate than the reproduction of mesophytic hardwood species?
3. Does the proportion of oak reproduction increase relative to that of mesophytic hardwood species postfire?
4. Does oak reproduction grow as fast as that of mesophytic hardwood species postfire?
5. Does prescribed fire reduce the density of midstory trees of all species?

Meta-analysis results indicated that prescribed fire tended to facilitate the establishment of new oak seedlings from acorns, but the trend was not statistically significant (Fig. 22). Oak reproduction sprouted at a higher rate postfire than the reproduction of mesophytic hardwoods (Fig. 23). However, oak's superior sprouting ability did not always translate into increased relative abundance in the regeneration pool (Fig. 24). In the postfire environment, the height

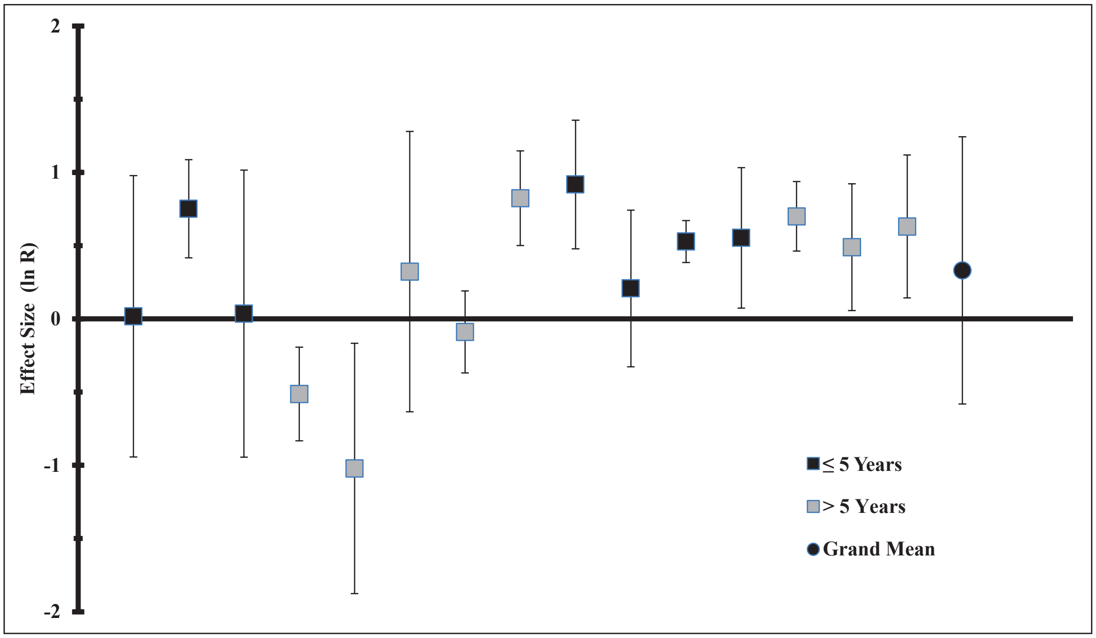

Figure 22.—The establishment of new oak seedlings (log response ratio ± 95% confidence interval) following short-term (≤5 years) and long-term (>5 years) prescribed fire studies. Log response ratios significantly above zero indicate an increase in the density of new oak seedlings. Log response ratios significantly below zero indicate a decrease in density. Ratios that are not significantly different from zero indicate no change in the density of new oak seedlings.

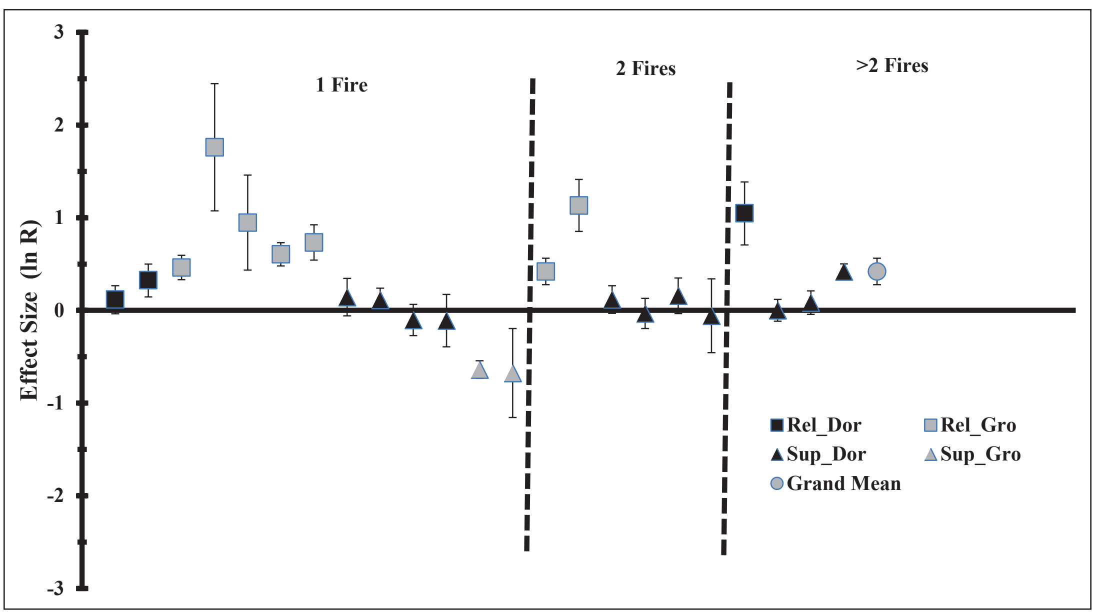

Figure 23.—The relative sprouting (log response ratio ± 95% confidence interval) of released (Rel) and suppressed (Sup) oak reproduction in comparison to mesophytic hardwood reproduction following dormant season (Dor) and growing season (Gro) prescribed fires conducted throughout the eastern United States. Log response ratios significantly above zero indicate that the oak reproduction sprouted postfire at a higher rate than the mesophytic reproduction. Log response ratios significantly below zero indicate oak reproduction had a lower postfire sprouting rate than mesophytic reproduction. Ratios that are not significantly different from zero indicate that the survival rates of the two species groups were equivalent.

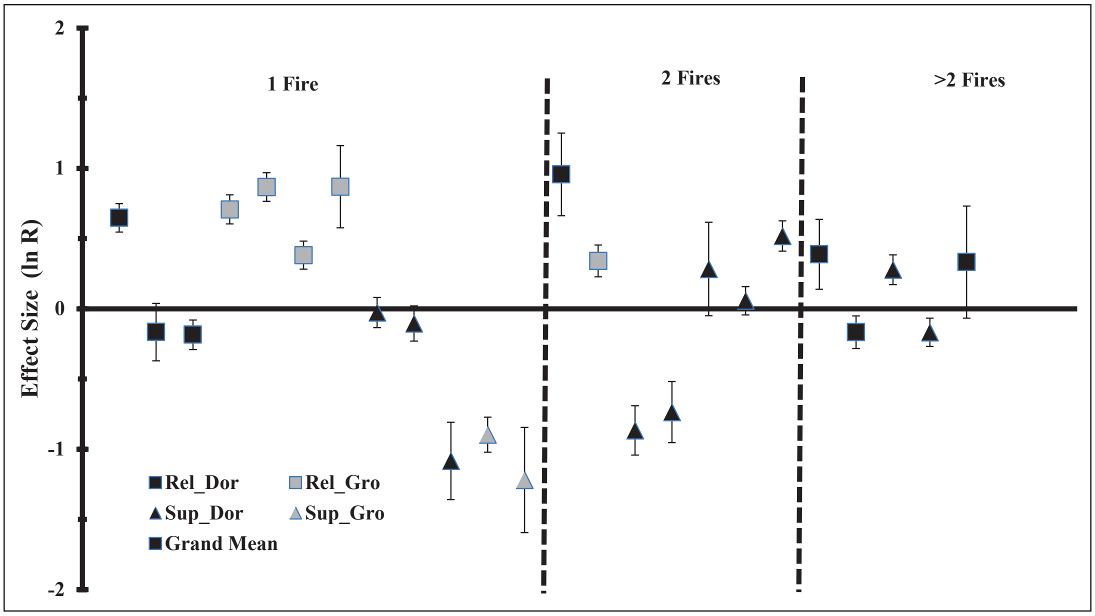

Figure 24.—The relative abundance (log response ratio ± 95% confidence interval) of released (Rel) and suppressed (Sup) oak reproduction following dormant season (Dor) and growing season (Gro) prescribed fires conducted throughout the eastern United States. Log response ratios significantly above zero indicate that the proportion of oak reproduction increased in the regeneration pool. Log response ratios significantly below zero indicate that the proportion of oak reproduction decreased in the regeneration pool. Ratios that are not significantly different from zero indicate that the proportion of oak did not change.

growth of oak reproduction was similar to that of many competing mesophytic hardwood species (Fig. 25). Within the usual range of conditions under which prescribed fires are conducted in eastern oak forests, a fire has limited ability to kill stems (Fig. 26).

After reviewing the fire-oak publications presented in Tables 4, 5, and 6, and the results of the meta-analysis, several findings and trends emerged that will be useful to managers of oak-dominated ecosystems.

- **Many factors influence the outcome of a prescribed fire on oak regeneration.** Among these, the important biological factors are the developmental stage of the oak stand and the degree of root development of the oak reproduction. Important fire factors are season of burn, fire intensity, and their interaction. Finally, critical site factors include topography and the disturbance history of the stand.
- **In mature stands (understory re-initiation stage), as the number of fires increase, so does the benefit to oak.** Single fires and the initial burn of a multi-fire sequence provide little, if any, benefit to the oak reproduction and may actually be detrimental in the short term. Conversely, multiple burns spread over a decade or more will generally benefit the oak component of the regeneration pool via an improved seedbed for oak seedling establishment and enhanced understory light conditions for the subsequent growth of the new seedlings and any existing oak reproduction.
- **In young stands (initiation stage), single fires can rapidly benefit the oak reproduction.** This is likely due to differences in root development between the oaks and the competing mesophytic hardwoods that give the oaks a higher postfire sprouting probability.

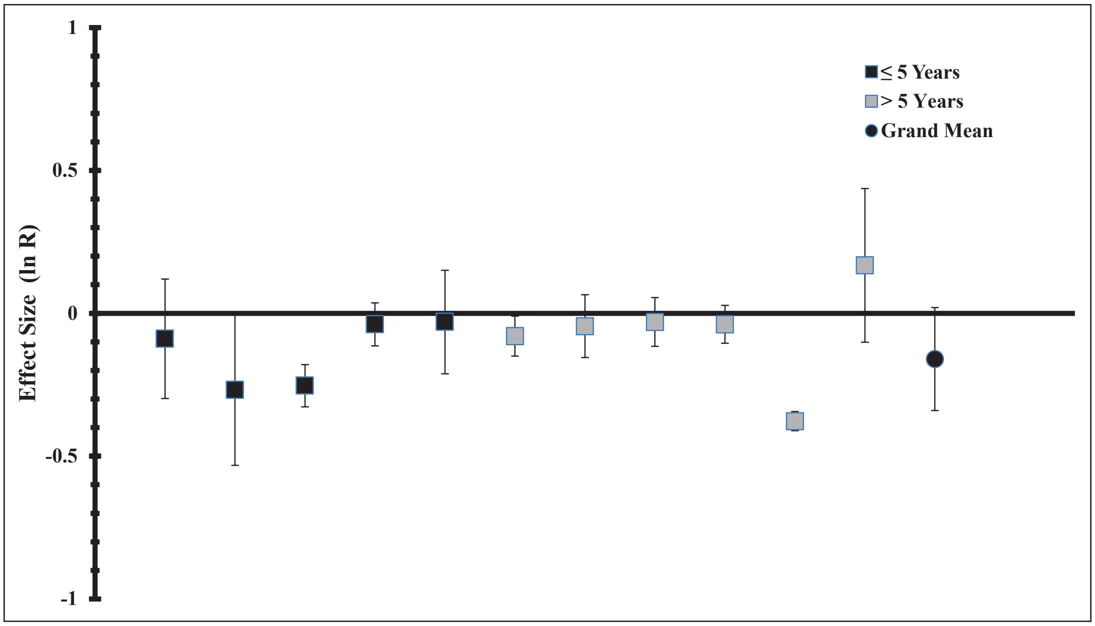

Figure 25.—The relative height (log response ratio ± 95% confidence interval) of oak reproduction in comparison to mesophytic hardwood reproduction following short-term (≤ 5 years) and long-term (> 5 years) prescribed fire studies conducted throughout the eastern United States. Log response ratios significantly above zero indicate that the oak reproduction was taller than the mesophytic reproduction postfire. Log response ratios significantly below zero indicate that the oak reproduction was shorter than the mesophytic reproduction postfire. Ratios that are not significantly different from zero indicate that the heights of the two species groups were equivalent.

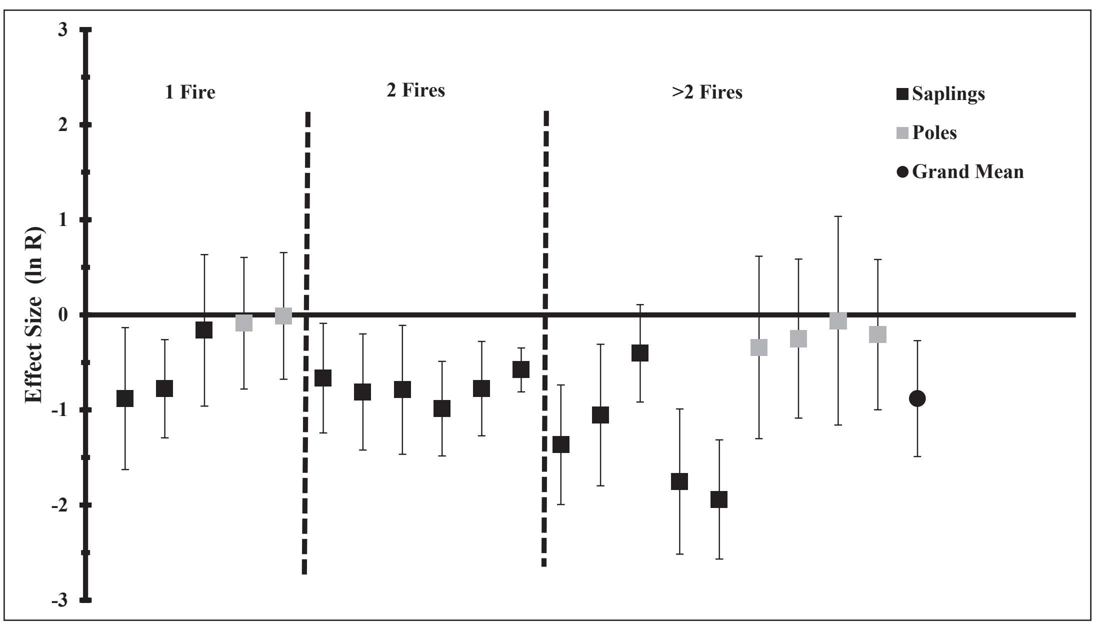

Figure 26.—The reduction of pole and sapling stem density (log response ratio ± 95% confidence interval) following prescribed fires conducted throughout the eastern United States. Log response ratios significantly below zero indicate that the number of midstory stems decreased while ratios that are not significantly different from zero indicate that the postburn densities were unchanged.

- **In immature stands (stem exclusion stage), prescribed fire can increase the relative proportion of oak**. However, there will be large economic losses due to bole damage to the trees that survive the fire, and due to stem defects (crook and sweep) of the new sprouts.
- **Among the various eastern tree species, postfire sprouting ability of the reproduction varies widely.** Some species are nonsprouters (eastern hemlock and white pine), some are poor sprouters (sweet birch and yellow-poplar), some are moderate sprouters (red maple), and some are excellent sprouters (oak and hickory). The sprouting ability of a species is a function of its capability to form dormant basal buds coupled with its germination strategy (epigeal or hypogeal), its juvenile growth strategy (root-centric or stem-centric), and its shade tolerance (i.e., the optimal light regime for juvenile growth). Sprouting ability is also influenced by season of burn, fire intensity, and their interaction.
- **Growing season fires will have more impact (i.e., kill more stems) than dormant season fires because the vegetation is physiologically active.** Similarly, multiple fires kill more stems than single fires due to accumulated damage on midstory and overstory trees. In general, a single dormant season fire will have the least impact on forest structure while multiple growing season fires will have the most impact. Multiple dormant season fires and single growing season fires will have an intermediate impact. Within any of these, fire intensity will also play a role as hotter fires have more impact than cooler fires.
- **Immediate mortality from a single fire is typically confined to the regeneration layer and small saplings (<3-inch d.b.h.).** Midstory trees, large saplings (3- to 6-inch d.b.h.), and pole-size trees (6- to 10-inch d.b.h.) are periodically killed and some may succumb to delayed mortality. Overstory trees (>11-inch d.b.h.) are generally unscathed unless there is an accumulation of fuel at or near their bases.
- **Long-term fire studies in young stands are needed.** We found only 10 fire studies done in oak shelterwoods or recently-regenerated oaks stands, and just one of them reported results more than 10 years postfire. While the vast majority of these studies reported positive results for the oak reproduction, more research is needed to understand other ramifications of this approach.
- **Prescribed burning can make the oak regeneration process more difficult.** Fire kills many of the acorns already on the ground. Small oak seedlings with undeveloped root systems are virtually defenseless against a fire, especially a growing season burn. Prescribed fires can cause a large influx of new seedlings from seed stored in the forest floor, exacerbate invasive species problems, and incite excessive browsing by white tail deer.

CHAPTER 5: GUIDELINES FOR USING FIRE IN OAK ECOSYSTEMS

The fire-oak hypothesis is fundamentally sound based on the review of the pertinent literature in the preceding three chapters of this report. Fire history research clearly shows that periodic fires have been an integral part of the disturbance regime of upland oak[1] ecosystems throughout eastern North America for millennia. American Indians were the primary ignition source of these fires, but lightning also contributed to fires. Basic silvics research shows that oaks have several physical characteristics that give them a survival advantage in a periodic fire environment as well as allowing them to exploit the postfire environment. Recent fire research demonstrates that prescribed fire can be used in some situations to promote the regeneration of oak. In this chapter, we synthesize the findings presented in the previous chapters, especially Chapter 4, into guidelines for using prescribed fire to regenerate and restore upland oak ecosystems in eastern North America.

Essential Background Information

To correctly use prescribed fire in oak forest management, one must first understand even-aged stand development (Fig. 27) (Oliver and Larson 1990), the oak regeneration process (Johnson et al. 2009), and how they interrelate (Arthur et al. 2012). The canopies of many eastern forests are even-aged or irregular-aged and are dominated by two cohorts of oak resulting from the disturbance pattern that occurred widely from the mid-1800s to the early 1900s (Brose et al. 2001). During those decades, much of the eastern hardwood biome was cleared for agriculture or to provide raw materials for the Industrial Revolution and a rapidly-growing nation. In many locations, wildfires followed forest clearing, and both of these disturbances ceased rather suddenly due to exhaustion of forest resources and conservation efforts. Consequently, the burned cutover forests were left to regrow, resulting in young, even-aged hardwood forests (stand initiation stage) dominated by oaks. With time, these young forests grew into and through the stem exclusion stage and are currently mature stands in the understory re-initiation stage. For them to be regenerated to oak–that is to begin the stand initiation stage again–they must successfully pass through the regeneration process in a way that favors oaks. Otherwise, they will convert to a different forest type.

The oak regeneration process, or the procedure by which mature oaks are replaced by their progeny, consists of three phases and an event. The three phases include acorn production, establishment of new oak seedlings, and development of the seedlings into competitive-sized oak reproduction (Fig. 28). The event is an adequate, timely release (Johnson et al. 2009, Loftis 2004). The oak regeneration process usually takes at least a decade due to the sporadic occurrence of large acorn crops and the emphasis on root development by young oak seedlings. Oaks typically have heavy masting events every 5 to 10 years depending on species and location (Burns and Honkala 1990). Acorn crops are subject to numerous environmental factors that can slow this phase of the regeneration process or force it to start again (Arthur et al. 2012, Johnson et al. 2009). For example, diseases, insects, and weather can ruin acorns before they ever fall from the trees or, once on the ground, acorns can be destroyed by these same factors or consumed by wildlife. Once an oak seedling cohort forms, these seedlings grow slowly for several years as they emphasize root development if adequate resources, especially light, are

[1]Scientific names of the flora and fauna are listed in the Appendix.

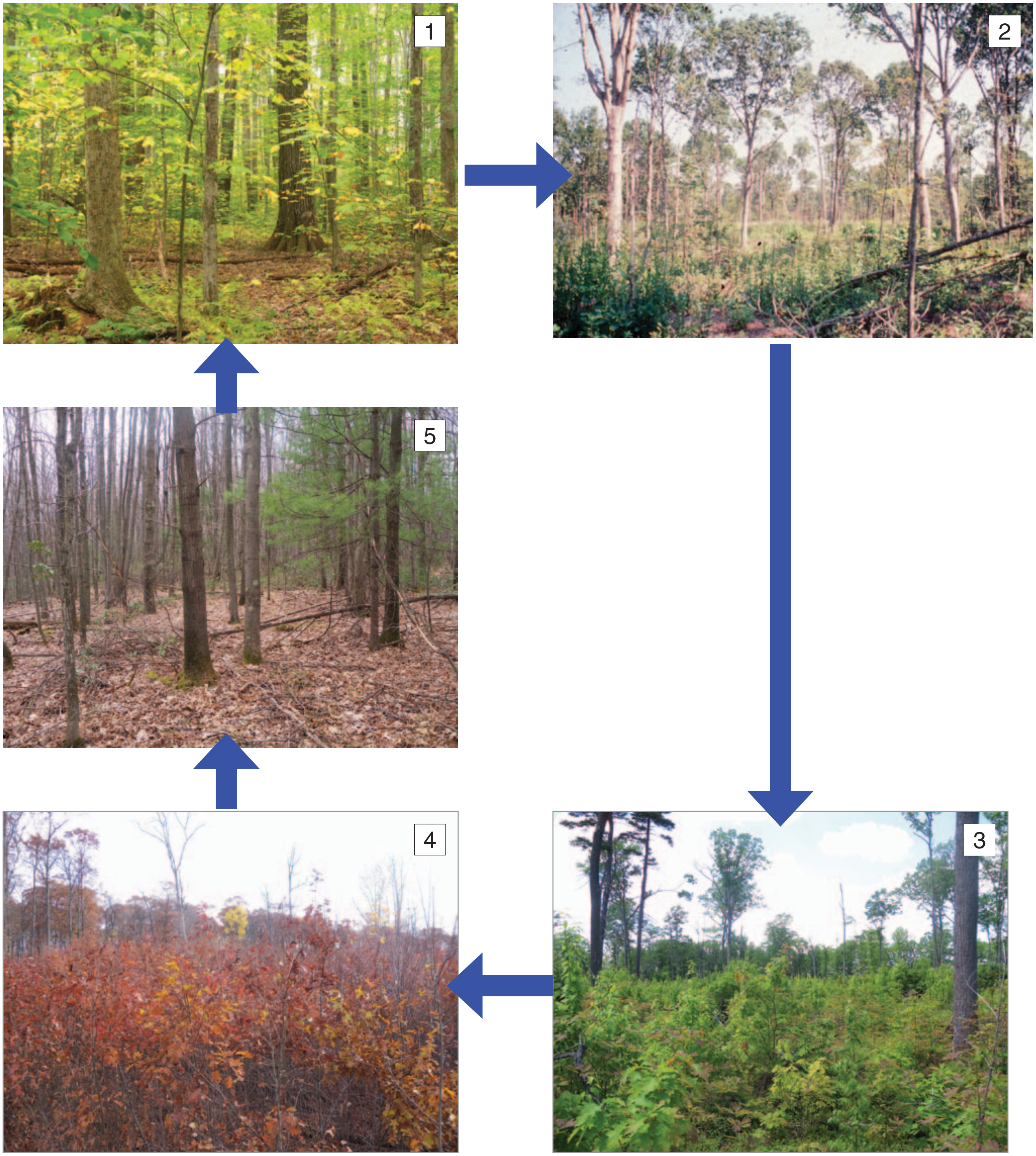

Figure 27.—The even-aged stand development model with a two-cut shelterwood sequence. Stages are (1) mature stand or understory re-initiation, (2) first removal harvest, (3) final removal harvest, (4) young stand or stand initiation, and (5) immature stand or stem exclusion. Generally, oak forests need at least 75 years to complete this cycle. Photos by Patrick Brose, U.S. Forest Service.

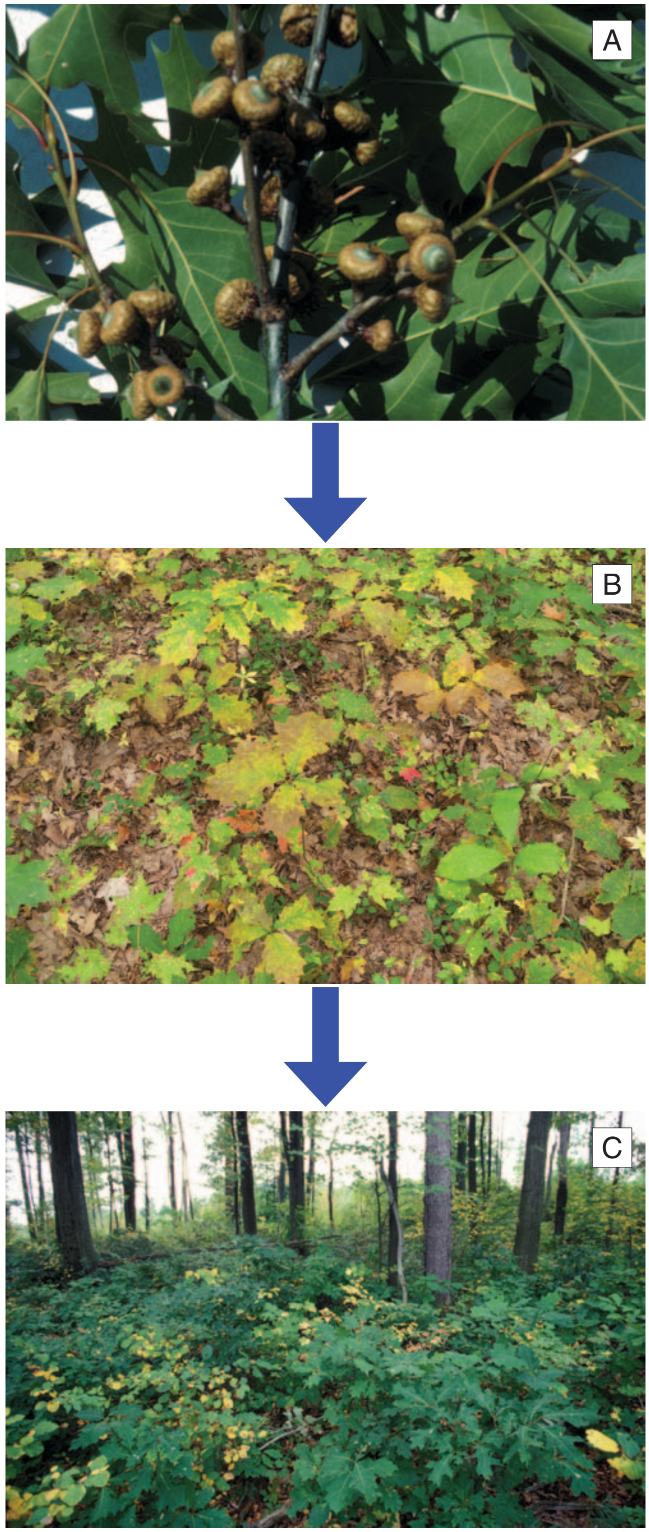

Figure 28.—The oak regeneration process. The three phases are (A) acorn production, (B) oak seedling establishment, and (C) development of competitive-sized oak reproduction. Generally, oak forests need 10 to 25 years to move through the entire regeneration process. Photos by Patrick Brose, U.S. Forest Service.

sufficient for oak survival and growth. Like acorn production, the root development phase of the regeneration process can be slowed, stalled, or forced to begin again due to numerous environmental factors. Preeminent among these are the amount of understory shade, deer browsing, and the amount and composition of competing vegetation (Brose 2011a, Miller et al. 2004). Eventually, the oak reproduction becomes large enough to successfully compete on the site and can be released by harvesting the overstory trees. Because of all these factors, the oak regeneration process typically lasts 10 to 25 years (Carvell and Tryon 1961, Clark and Watt 1971, Sander 1972).

In the even-aged stand development model, the oak regeneration process fits between the understory re-initiation stage and the stand initiation stage with some overlap into both stages (Fig. 29). The oak regeneration process begins in the understory re-initiation stage when the mature oaks produce acorns, some of which become seedlings. Once there is a sufficient density of oak seedlings to begin a sequence of regeneration harvests, the parent oak stand begins transitioning from the understory re-initiation stage to the stand initiation stage. This transition may be abrupt (the overstory is completely removed by one harvest) or gradual (the overstory is removed by a shelterwood sequence of two or more partial harvests). Oak shelterwoods have elements of both stages of stand development. Overstory trees are still present, but their influence on the reproduction diminishes as the degree of cutting increases. The final removal harvest marks the end of the oak regeneration process and places the new stand in the initiation stage.

The first steps of using prescribed fire in oak forest management are to decide what type of oak forest is desired in the future and determine where the prospective stand is in the even-aged development model and the oak regeneration process. The desired future oak forest is dictated by the management objectives while the current condition is ascertained by an inventory. The inventory is an absolute necessity if the management objective is a future oak-dominated stand similar in composition to the current one. The inventory can be a simple walk-through evaluation by a forester experienced with local conditions, a comprehensive, systematic assessment such as those done in conjunction with prescriptive expert systems like SILVAH (Brose et al. 2008), or something in between. The inventory must provide basic information about the overstory, understory, and regeneration conditions to determine oak regeneration potential, as well as to identify potential obstacles to forest renewal and sustainability. After an inventory reveals where the stand is at in its development and in the oak regeneration process, the correct type of fire can be prescribed and coordinated with other silvicultural practices to meet the management objectives.

From our review of the oak-fire literature and the results of our meta-analysis (Brose et al. 2013b), we have determined three categories of prescribed fire that are appropriate in oak ecosystems: (1) seedbed preparation burning, (2) release burning, and (3) ecological restoration burning. The rest of this chapter describes these categories of prescribed fire, provides guidelines on how to conduct these types of fires, and presents pitfalls that can negate the desired outcome of the prescribed burn.

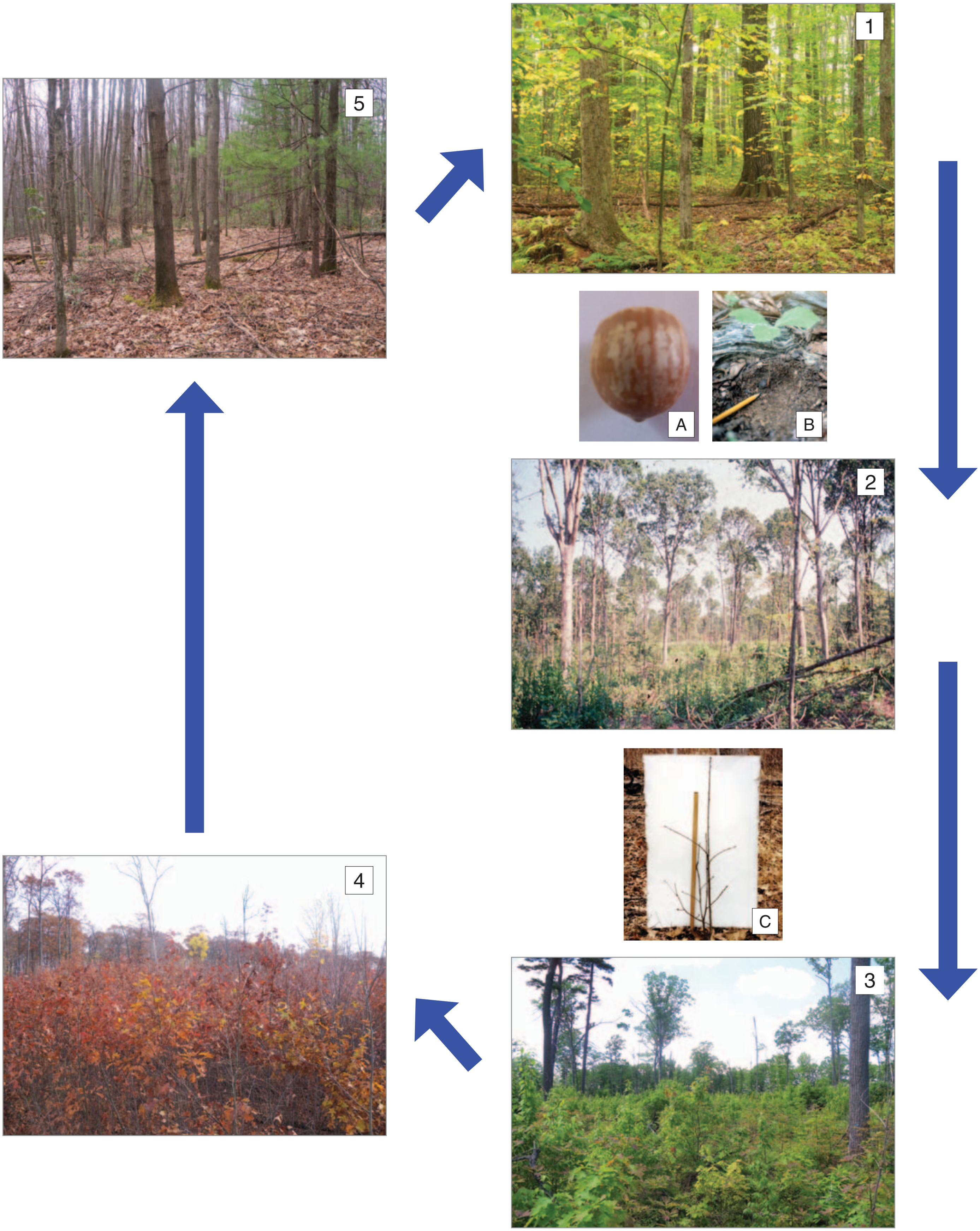

Figure 29.—The merger of the even-aged stand development model and the oak regeneration process. Note that acorn production (A) and oak seedling establishment (B) occur before the first removal harvest (2), and the final removal harvest (3) occurs after the oak reproduction has become large enough to be competitive (C). Photos by Patrick Brose, U.S. Forest Service.

Figure 30.—The three characteristics of oak stands needing seedbed preparation burning are a lack of oak seedlings in the regeneration layer (top left), an understory dominated by non-oak species (top right), and thick duff and litter layers (right). Photos by Patrick Brose and Robert Long, U.S. Forest Service.

Seedbed Preparation Burning

Seedbed preparation burning takes place in mature oak stands that are at the beginning of the oak regeneration process. These stands are characterized by three conditions (Fig. 30). First, oak reproduction is absent or is so scarce as to be a nonfactor in regeneration planning. In addition, the understory contains an abundance of woody non-oak species such as American beech, mountain laurel, red maple, striped maple, and witch-hazel that cast a dense shade on the forest floor. Finally, thick litter (Oi horizon) and duff (Oe and Oa horizons) layers are present. The objective of seedbed preparation burning is to reduce or eliminate the dense shade and thick litter so a future acorn crop can find a hospitable seed bed resulting in the formation of an oak seedling cohort of sufficient density to begin moving forward through the oak regeneration process.

Prescribed fire planning for seedbed preparation burns in oak stands is rather simple and straightforward. The proposed burn unit is delineated by natural or man-made boundaries that function as the control and contingency lines. Anderson Fuel Model 09 (AFM-09) described in Anderson (1982) adequately portrays the fuel bed characteristics and provides reasonable fire behavior estimates for the environmental conditions under which most prescribed burns are conducted in eastern North America (Brose 2009a). The exception to this is when the oak stand has an understory shrub layer of ericaceous (heath) species such as blueberry or mountain laurel (Fig. 31). If the heath shrub is deciduous, such as blueberry, then AFM-06 is a good choice for planning purposes. Evergreen heath shrubs like mountain laurel are not well characterized by

Figure 31.—An oak forest with a dense ericaceous (heath) understory of blueberry, huckleberry, and mountain laurel. These shrubs increase fuel loadings that, in turn, lead to intense fires. Photo by Patrick Brose, U.S. Forest Service.

Figure 32.—A fall prescribed fire in eastern Pennsylvania in an oak stand with a dense heath understory. Flame lengths are 5 to 10 feet. Photo by Patrick Brose, U.S. Forest Service.

any of the 13 AFMs, but AFM-05 is a reasonable representation and AFM-10 and AFM-04 will provide a lower and upper bound on what to expect for minimum and maximum fire behavior. Generally, strip-head fire is the ignition pattern because the objective is litter and understory strata reduction without causing significant damage to the overstory trees. Flame lengths are generally <2 feet and rates-of-spread are <5 feet per minute, but heath shrubs can increase these parameters to 5 to 10 feet and 5 to 10 feet per minute (Fig. 32). See Waldrop and Goodrick (2012) for more details on planning and conducting prescribed fires. Finally, season of burn is not strongly important in seedbed preparation burning, although growing season fires tend to cause more mortality to the understory than dormant season fires.

Figure 33.—An oak stand in western South Carolina lacking midstory and understory layers due to repeated growing season fires. Note the dense vegetation in the unburned area at the back of the photo. Photo by David Van Lear, Clemson University.

Seedbed preparation burning provides several benefits to the oak forest including virtually eliminating the litter layer and thinning the duff layer. Generally, fire consumes more than 90 percent of the litter layer (Brose 2009a; Crosby and Loomis 1974; Loomis 1975, 1977). A thick litter layer can be a barrier to oak seedling establishment (Arthur et al. 2012, Johnson et al. 2009), and blue jays and tree squirrels prefer caching acorns in areas of thin leaf litter (Johnson and Adkisson 1986, Steele and Smallwood 2002). The impact of fire on the thickness of the duff is less drastic as this layer generally retains some moisture that retards its consumption. Still, the duff layer can be decreased by 10 to 20 percent by seedbed preparation burning through direct consumption and subsequent accelerated decomposition (Loomis 1975, Van Lear and Danielovich 1988). Another major impact of seedbed preparation burning is the reduction of the mid- and understory strata and the accompanying dense shade (Fig. 33). Fires of moderate intensity (flame lengths ~1 foot) can generally girdle stems with a diameter at breast height (d.b.h.) of <3 inches. Removing this tall advanced reproduction and small saplings creates an understory light regime of approximately 7 percent sunlight (Miller et al. 2004). This low level of sunlight improves oak seedling survival and initiates modest root development without eliciting germination en masse from the seed bank or creating a hospitable seed bed for light-seeded pioneer species. This level of shade from the overstory can limit the growth of shade intolerant reproduction and sprouts of existing advance reproduction that form after the fire.

Other benefits of seedbed preparation burning include recycling the nutrients stored in downed woody debris (Blankenship and Arthur 1999, Boerner 2000), stimulating the soil ectomycorrhizae community (Stottlemyer 2011), reducing the populations of some acorn insect pests (Lombardo and McCarthy 2009, Riccardi et al. 2004, Wright 1986), and xerifying the soil surface (Barnes and Van Lear 1998). As fire consumes the woody fuels, essential plant growth elements including Ca, K, Mg, and P are released back into the soil and are available for

Figure 34.—An oak stand in western Pennsylvania treated with one low-intensity, dormant season prescribed fire. Note the abundance of dense shade on the forest floor and the lack of control of the many sapling- and pole-sized stems. Photo by Patrick Brose, U.S. Forest Service.

other plants. Sequestered N is volatilized, but soil N increases due to increased soil microbial activity. The nutrient needs of new oak germinants are not yet well understood, but increased soil nutrient availability reduces the likelihood that low soil nutrient status is a limiting factor to their survival and growth. Additionally, fire raises soil pH slightly, further increasing nutrient availability. And for a still unclear reason, fire stimulates the growth and reproduction of ectomycorrhizae in the soil. These fungi form symbiotic relationships with the fine feeder roots of oak seedlings, enhancing the seedling's ability to absorb nutrients and water from the soil. Burning also affects numerous acorn insect pests such as weevils, Valentine moths, and gall wasps that attack acorns while they are still in the trees or once they have fallen to the ground. These insects spend part of their life cycle on the forest floor, and prescribed fire has been shown to reduce their impact on acorns. Finally, seedbed preparation burning xerifies or dries the surface layers of the soil so that it is a less hospitable seedbed for the germinants of many mesophytic tree species.

Despite the benefits of seedbed preparation burning, there are also drawbacks. First, reduction of leaf litter and understory shade can be insufficient and short-lived because the fire intensity may be insufficient to kill trees >3-inch d.b.h. and the litter layer can reaccumulate in 2 to 3 years (Fig. 34) (Crosby and Loomis 1974, Loomis 1975, Stambaugh and Guyette 2006). This is especially true for single, low-intensity, dormant season fires. Growing season fires reduce the midstory strata quicker and to a greater degree than dormant season fires (Barnes and Van Lear 1998, Waldrop and Lloyd 1991, Waldrop et al. 1987). Second, timing a seedbed preparation burn to shortly precede an acorn crop is impossible. Acorn crops cannot be reliably forecasted until mid-summer of the year they are going to occur (Koenig et al. 1994, Perry and Thill 1999,

Figure 35.—An oak stand in southern Ohio that has been treated with four prescribed fires over 15 years. Note the diffuse shade and the abundance of vigorous oak reproduction. Photo by Daniel Yaussy, U.S. Forest Service.

Sharp 1958, Whitehead 1969), so insufficient time for planning or uncooperative weather in the season before acorn drop can impact the burn. Alternatively, the fire may be successful but the acorn crop may be a failure due to any one of the many factors that can cause acorn abortion, resulting in fewer acorns benefitting from the seedbed preparation burning. For these reasons, seedbed preparation burning usually involves several fires spread over 10 to 15 years to create the open understory, maintain a suitable seedbed, and eventually coincide with an acorn crop (Fig. 35). Repeat fires are also more effective in reducing density of competitor sprouts in the understory (Brose et al. 2013b). Patience and persistence are necessities when using fire for seedbed preparation (Weigel et al. 2012).

Other drawbacks to seedbed preparation burning are the loss of viable acorns and small oak seedlings (Auchmoody and Smith 1993, Cain and Shelton 1998). In stands with acorns on the ground or a recently-formed oak seedling cohort, refrain from burning and instead use one of the individual stem herbicide techniques to reduce understory shading (Brose et al. 2008, Kochenderfer et al. 2012). If herbicides are not an option, wait several years before burning so that the acorns can germinate and the new oak seedlings have some time to develop their root systems, if there is enough light. In deep shade, oak seedlings begin declining once acorn reserves are exhausted (Brose 2011a, 2011b; Crow 1992; Dey and Parker 1997b; Loftis 1988; Schuler et al. 2013). If this is the case, use dormant season burns to minimize oak seedling mortality. Finally, seedbed preparation burning can attract deer that subsequently feed on acorns and new oak seedlings and stimulate the establishment and spread of some native and nonnative invasive plant species such as hay-scented fern and tree-of-heaven if they are present onsite or in adjoining areas (Fig. 36) (Rebbeck 2012).

Figure 36.—An overabundance of deer (left) and invasive plant species (right) can cause problems when using prescribed fire to regenerate oak forests. Photos by David Marquis (retired) and Patrick Brose, U.S. Forest Service.

Figure 37. —Shelterwood stands (left) and newly-regenerated stands (right) are appropriate for release burning. Photos by Patrick Brose, U.S. Forest Service.

Release Burning

Release burning is a type of prescribed fire used in oak stands that are nearing the end of the oak regeneration process to lessen or stop an impending shift in species composition from oak to mesophytic hardwoods. Candidate stands have three key characteristics. The stands are on intermediate to high quality sites (oak site index$_{50}$ 65 to 80), they are undergoing a shelterwood sequence or have just been regenerated via a final harvest (Fig. 37), and they contain an abundance of vigorous oak reproduction overtopped by taller competing regeneration of mesophytic hardwoods.

Oak reproduction suitable for prescribed burning is typically >1 foot tall with a root collar diameter ≥0.5 inch. Adequate oak density can range from several hundred to several thousand stems per acre with the larger densities needed on the higher quality sites. Density varies by management objectives for future oak stocking at maturity and also depends on the ability to do additional release treatments at critical stand developmental stages such as at the onset of stem exclusion. Spatial distribution or stocking of the oak reproduction needs to be widespread throughout the stand so that at least 50 percent of the inventory plots contain vigorous oak reproduction. The reproduction of the competing mesophytic hardwoods will outnumber and overtop the oak reproduction by several thousand stems that are several feet taller, especially on the better quality sites. When oak shelterwoods and final harvest stands have the above characteristics, they are candidate stands for prescribed burning to release the oak from competition as described below.

The Shelterwood-Burn Technique

Correctly implementing the shelterwood-burn technique (Brose et al. 1999a, 1999b) is more than simply applying fire to a partially-cut oak stand. The proper application of the technique actually begins before the shelterwood harvest while the stand is still uncut or has had a low/midstory shade reduction treatment. The first step addresses two questions: (1) is there enough oak reproduction at this time to proceed with a regeneration sequence given the future oak stocking goal, site quality, and obstacles to stand renewal, and (2) can the stand be burned in approximately 5 years? If the first question is answered negatively, then you must wait to implement the shelterwood-burn technique until there is an adequate density of oak reproduction or institute underplanting to reach the desired density of oak reproduction (Dey and Parker 1997a, 1997b; Johnson et al. 2009). Also consider the appropriateness of implementing a seedbed preparation burn (see previous section). If the second question is answered negatively, then you must make alternative regeneration plans such as using the herbicide-shelterwood method which is largely a removal of the midstory and overstory trees in the lower crown classes by mechanical or chemical methods to promote the growth of the abundant but small oak advance reproduction (Loftis 1990). If both questions are answered positively, then proceed with the technique by planning and conducting the first removal cut of a two-stage shelterwood sequence.

The purpose of the first removal cut is to create the understory light conditions (30 to 50 percent of full sunlight) needed to promote rapid root development of the oak reproduction while slowing the height growth of the competing mesophytic regeneration (Fig. 38) (Brose 2011a). Because fire will be used in a few years, planning and conducting this harvest requires some extra attention. First, lay out access roads and skid trails so they can double as fire control lines in the future. This will expedite the preparation for the prescribed fire, decreasing one of its costs. Second, create a 50 percent open canopy by harvesting the low-quality stems, undesirable species, and some financially-mature trees (Fig. 39). This is more than a commercial harvest. It is necessary to remove unmerchantable overstory trees in the lower crown classes and any midstory trees to achieve the 30 to 50 percent of full sunlight. Be sure to cut all unmerchantable trees and larger saplings, especially those >3-inch d.b.h., because they have higher probabilities of surviving a low intensity fire intact. Cut stems have a high likelihood of sprouting, but the sprouts will be susceptible to topkill in a subsequent burn. Alternatively, the midstory and noncommercial trees can be stem injected with herbicides (Kochenderfer et al. 2012). In terms of basal area, the residual will range from 50 to 80 square feet per acre with the higher residual levels being left on the better quality sites. The ideal leave trees are high quality oaks that are approximately 15- to 17-inch d.b.h. Trees of this diameter will increase substantially in size and value over the next 5 to 10 years, especially if they move from Grade 2 saw logs to Grade 1. It

Figure 38.—Eight-year-old chestnut oak seedlings grown in shelterwoods of varying residual relative densities. Those on the left were in 70 to 90 percent relative density while those on the right were in 20 to 50 percent relative density. Photo by Patrick Brose, U.S. Forest Service.

Figure 39.—An oak shelterwood in northern Pennsylvania with 50 percent residual basal area. This is the ideal structure for developing vigorous oak reproduction that will be treated with a release burn in a few years. Photo by Patrick Brose, U.S. Forest Service.

Figure 40.—In the shelterwood-burn technique, slash must be managed so it does not accumulate at the base of residual crop trees (left). If it does, the crop tree will be badly damaged or killed by the release burn (right). Photos by Patrick Brose, U.S. Forest Service.

is unlikely that there will be enough ideal oaks per acre to meet the recommended residual basal area so other trees will have to be kept as leave trees, but be sure not to keep any undesirable species that are prolific seed producers such as black birch and yellow-poplar. Finally, manage the slash to protect the residual crop trees (Fig. 40). The harvest will create concentrations of slash, and such “fuel jackpots” within 10 feet of the bases of residual crop trees can create and hold an intense fire that will likely damage or kill them (Brose and Van Lear 1999). Be sure the logging contract stipulates that directional felling is used to prevent placing tree tops near the bases of residual crop trees or that such slash is removed as part of the harvesting operation (Brose 2009b).

The first removal cut is followed by a multi-year waiting period of 4 to 7 years (Fig. 41). This period is important for several reasons. First and foremost, this is when the oak reproduction develops root systems, a necessary precursor to their ability to sprout postfire (Brose 2008, 2011a; Brose and Van Lear 2004). The wait also allows the seed bank in the forest floor to germinate, at least in part (Schuler et al. 2010). The resultant flush of new reproduction probably will contain some seedlings that are potential, long-term competitors to oak such as black birch and yellow-poplar. As new seedlings, they are virtually defenseless against a prescribed fire. Additionally, this wait allows the fuel bed to develop as the logging slash settles and dries and leaf litter accumulates from the residual canopy trees. Finally, the waiting period allows the residual crop trees to increase in volume and value, making the final harvest more profitable. Leave the stand undisturbed until the oak seedlings have root collar diameters ≥0.50 inch and are at least 2 feet shorter than the competing mesophytic hardwood reproduction. These conditions usually develop within 4 to 7 years, depending on site quality.

The purpose of the prescribed fire is to select for the oak seedlings and against the mesophytic hardwood reproduction based on the difference in root development strategies between the two species groups. A hot spring burn provides the optimal combination of fire intensity and season of burn for maximum benefit to the oak seedlings (Brose 2010, Brose and Van Lear 1998, Brose et al. 1999a). Because such a fire will occur in an oak shelterwood, careful planning is a must. Use AFM-06 or AFM-10 to represent the fuel loadings of oak shelterwoods to predict expected fire behavior (Brose 2009a). Identify the residual crop trees in danger of

Figure 41.—A 4-year-old oak shelterwood in central Virginia ready for a growing season release burn. Note the dense regeneration layer and the degree of leaf expansion by the understory and overstory trees. Photo by Patrick Brose, U.S. Forest Service.

Figure 42.—The ideal time to conduct a release burn is in mid spring when the oak seedlings are still dormant (left) but the competing hardwoods have already expanded their leaves by at least 50 percent (right). These two photos were taken within 30 feet of each other on May 12, 2011 in northern Pennsylvania. Photos by Patrick Brose, U.S. Forest Service.

fire damage due to logging slash close to their bases and take preventative measures to protect them (Brose 2010). Strive to burn at the ideal time in the spring season when the mesophytic hardwood reproduction has expanded their leaves at least 50 percent but the oak seedlings still have closed buds and the overstory is still dormant (Fig. 42). The ideal time to burn varies by location and elevation as well as from year to year. For example, the optimal burn window generally occurs in late April in southern Ohio but is in mid-May in northern Pennsylvania. An

Figure 43.—A moderate-intensity spring fire in central Virginia. Flame lengths are 2 to 4 feet. Photo by Patrick Brose, U.S. Forest Service.

extended winter or an early spring will shift this window backward or forward and will shorten or extend its duration. Finally, plan a hot prescribed fire. Flame lengths need to be ≥2 feet with rates of spread ranging from 3 to 7 feet per minute (Fig. 43). Although this combination of fire intensity and season of burn has consistently produced excellent results in shifting the composition of the regeneration pool towards oak, burning outside the hot mid-spring window can also benefit oak, but to a lesser degree (Brose 2010, Brose et al. 1999a). Cooler fires and those conducted earlier in the spring provide less control of competing mesophytic hardwoods, and burns done after leaf expansion of the oak reproduction can reduce their survival and decrease their postfire height growth. See Waldrop and Goodrick (2012) for more details on planning and conducting prescribed fires.

When done properly, the shelterwood-burn technique will provide several benefits to the oak reproduction (Brose 2010, Brose and Van Lear 1998, Brose et al. 1999a). It will kill more mesophytic hardwood regeneration than oak reproduction, thereby increasing the relative abundance of oak in the advance regeneration pool (Fig. 44). Sprouting oaks will improve in stem form and rate of height growth (Fig. 45). Nutrients stored in the leaf litter and slash will

Figure 44.—The same stand shown in Figure 43, but several weeks later. The dead saplings are yellow-poplar and red maple while the green sprouts are oak and hickory. The relative abundance of oak and hickory increased from 10 to 70 percent in the regeneration pool and this dominance continued as the new stand grew into saplings. Photo by Patrick Brose, U.S. Forest Service.

Figure 45.—Prescribed fire can improve stem form and accelerate height growth. The left photo shows a single red oak sprout replacing the forked parent stem. The right photo shows the same sprout 15 years later as a vigorous, well-formed sapling. Photos by Patrick Brose, U.S. Forest Service.

be released back into the forest floor for subsequent use by the sprouting oaks (Blankenship and Arthur 1999, Boerner 2000). The ectomycorrhizae in the forest floor will be stimulated (Stottlemyer 2011). Berry-producing shrubs such as blueberry, huckleberry, and blackberry will be reinvigorated or germinate from seed stored in the forest floor. Besides the food benefit to wildlife, blackberry may help the development of oak sprouts by slowing the height growth of mesophytic hardwood seedlings and inhibiting the spread of ferns. It also provides an alternative supply of browse for deer and hiding cover for oak reproduction, potentially reducing deer browsing pressure on oaks.

Based on our collective experience, we see six common mistakes committed by land managers implementing the shelterwood-burn technique. They are:

- Making the first removal cut before an adequate density of oak reproduction is established.
- Opening up the canopy less than 50 percent with the first removal cut.
- Leaving slash accumulations near the bases of residual crop trees rather than mitigating this situation prior to burning.
- Burning before the oak reproduction develops sufficient roots and before the reproduction is overtopped by competing mesophytic hardwood regeneration.
- Burning earlier in the spring than is recommended.
- Conducting a low-intensity fire rather than a moderate- to high-intensity fire.

Committing any of these mistakes will likely necessitate additional prescribed fires or other silvicultural treatments to regenerate oak and avoid undesirable results at the end of the regeneration process.

The shelterwood-burn technique does have some drawbacks. The residual crop trees are at risk for fire damage and mortality (Brose and Van Lear 1999). This risk is both real and perceived because even though a veneer-quality oak is not damaged by the fire, potential buyers may pay less money for it because of the threat of staining. Larger red oaks (>11-inch d.b.h.) scarred by fire can lose up to 10 percent of the value in the butt log within 15 years of burning (Marschall 2013). The fire can also kill small oak reproduction that have not yet developed large enough root systems necessary for vigorous postfire sprouting (Gottschalk et al. 2013). If native and nonnative invasive plant species are in the burn unit, they may expand in coverage or they may seed in from adjoining areas (Rebbeck 2012). Deer are attracted to burned areas because the sprouting hardwoods are especially palatable and nutritious. In addition, mid-spring prescribed fires are probably disruptive to ground-nesting birds such as ruffed grouse, wild turkey, and several species of neotropical songbirds and are potentially lethal to herpatofauna just emerging from winter hibernation (Beaupre and Douglas 2012).

Postharvest Burning

One approach to mitigating the fire damage risk to crop trees in the shelterwood-burn technique is to conduct the final removal harvest before implementing the burn. This alternative is called postharvest burning (Brose 2013) and mimics the early 20th century disturbance regime that produced many of the current oak stands. If more time is needed for oak seedlings to get bigger before burning, the overstory harvest itself may provide a short-term release to the oak reproduction by crushing the competing mesophytic hardwood reproduction. Therefore, burning may be delayed for 1 to 3 years depending on site quality, but should be done before the height of the woody competition exceeds the oak reproduction by >2 feet and average stem d.b.h. increases to >3 inches. Postharvest burning has much in common with the shelterwood-burn technique. Both have the same objectives and prerequisites and the timber harvests are the same for both approaches. Postharvest burning should be done in mid-spring and strive for the same fire intensity as in the shelterwood-burn methods. One place they do differ is in planning. Postharvest burning has considerably higher fuel loads of 30 to 40 tons per acre (Fig. 46), so AFM-12 should be used in place of AFM-06 or AFM-10 (Brose 2009a). Anticipate flame lengths that are >5 feet (10 to 15 feet is not unusual) and a large smoke column, so plan accordingly for containment resources and smoke dispersal strategies (Fig. 46). See Waldrop and Goodrick (2012) for more details on planning and conducting prescribed fires.

Research on postharvest burning is not common in the scientific literature, but the existing publications indicate that the oaks in the regeneration pool benefit from fire at the end of the regeneration process (Carvell and Maxey 1969, McGee 1980, Ward and Brose 2004, Ward and Stephens 1989). Recent research confirms the findings of these studies (Fig. 47) (Brose 2013).

A somewhat different approach to postharvest burning is the fell-and-burn technique (Abercrombie and Sims 1986, Phillips and Abercrombie 1987). This method originated in the southern Appalachian Mountains and upper Piedmont regions in the 1980s as a way to regenerate or create pine-oak stands on low-quality sites (Fig. 48). As the name suggests, this

Figure 46.—Postharvest fuel loads of oak stands can reach 40 tons per acre (left) and burning them produces high-intensity fires and large volumes of smoke (right). Photos by Patrick Brose, U.S. Forest Service.

Figure 47.—A 5-year-old postharvest burn stand in northern Pennsylvania. Postharvest burning appears to create new, oak-dominated stands much like the shelterwood-burn technique. Photo by Patrick Brose, U.S. Forest Service.

Figure 48. —A young mixed oak-pine forest in western South Carolina created by the fell and burn technique. Note the diversity of tree species as indicated by their different fall colors. Photo by Thomas Waldrop, U.S. Forest Service.

Figure 49.—To start creating a mixed oak-pine stand via the fell and burn technique, completely harvest all the merchantable trees in the existing stand during the dormant season. Photo by Thomas Waldrop, U.S. Forest Service.

Figure 50.—Early in the growing season after the commercial harvest, fell all remaining hardwoods. Photo by Thomas Waldrop, U.S. Forest Service.

technique is a multi-step process. First, all the merchantable trees of the existing stand are harvested (Fig. 49). This is generally done in the winter. The following spring when the leaves are well to fully developed, all the nonmerchantable stems are felled (Fig. 50). Once their foliage is cured and their twigs and small branches dry, the site is broadcast burned (Fig. 51). This prescribed burn is conducted during the first summer following harvesting and after the hardwood stumps have sprouted, but within 1 to 2 days after a soaking rain (Fig. 52). This fire reduces the fuel loading, slows the height growth of oak and other hardwood sprouts,

Figure 51.—Conduct a growing season prescribed fire several weeks after the felling of the noncommercial hardwoods. The several-week wait is essential so that the hardwood litter has a chance to dry and the stumps have sprouted. Photo by Thomas Waldrop, U.S. Forest Service.

Figure 52. —A fell and burn stand shortly after the prescribed fire. Note the unconsumed large diameter boles, branches, and root mat and the general openness of the site. It is now ready for planting. The stump in the center of the picture will sprout again as will seedlings, seed stored in the soil, and a myriad of herbaceous species. Photo by Thomas Waldrop, U.S. Forest Service.

and prepares the site for the final step of planting the pine seedlings. Planting takes place the following winter, and the pines are planted at a fairly wide spacing (15 feet x 15 feet or greater). The preferred pine species varies by locale and includes loblolly pine in the Piedmont, shortleaf pine in the Ozarks, and pitch and white pines in the Appalachians (Fig. 53). Long-term research of this technique shows that the pine seedlings initially lag behind the hardwood sprouts in height growth but become dominant by year 7 to 10 (Waldrop 1997). By year 20, this method results in a mixed-species stand dominated by oaks and pines (Fig. 54) (Waldrop and Mohr 2012).

Figure 53.—A mixed oak-pine forest in the foothills of the southern Appalachian Mountains that was created 10 years earlier with the fell and burn technique. Depending on conditions and management objectives, the species of pine planted can vary among loblolly, longleaf, pitch, shortleaf, or white. Photo by Thomas Waldrop, U.S. Forest Service.

Figure 54.—Generally, the planted pines lag behind the hardwood sprouts for the first 10 to 20 years, but they eventually catch the oaks in height growth and form a mixed oak-pine ecosystem. Photo by Thomas Waldrop, U.S. Forest Service.

Figure 55.—An open oak woodland created by repeated prescribed fire. Note the diffuse shade and diverse herbaceous layer; two conditions sometimes described by early European settlers. Photo by Patrick Brose, U.S. Forest Service.

Ecological Restoration Burning

The previous two categories of prescribed burning (seedbed preparation and release) had as underlying assumptions timber production as the primary management objective and complete harvesting of the mature stand during the course of the regeneration process. In ecological restoration burning, timber harvesting is of secondary importance, and the driving objective is the reintroduction of periodic fire as an ecological process to restore or rehabilitate the structure and function of woodland and savanna ecosystems. Often, the foci of this type of prescribed fire are the creation and maintenance of a somewhat open stand structure and a diverse understory plant community. Fire is a critical part of the process necessary to sustain woodlands and savannas, for without it, these ecosystems would rapidly develop forest structure and function in eastern North America where precipitation is adequate and soils are sufficiently productive to support tree growth (Grimm 1983, Nuzzo 1986). Implicit within this objective is the development of a sufficient quantity of vigorous oak reproduction to replace the mature oaks when they succumb to natural mortality events. Ecological restoration burning is rather broad and inclusive but is well exemplified by prescribed fires used to create and maintain open oak woodlands, savannas, and shrubland habitats.

Open Oak Woodlands

Early European explorers and settlers frequently described parts of the eastern oak forest as open and park-like, consisting of large, widely-spaced trees with a diverse understory plant community (Fig. 55) (Bromley 1935, Day 1953, Maxwell 1910). While the amount and distribution of open oak woodlands is unknown, periodic fire is the most logical ecological process responsible for the creation and maintenance of this now rare habitat type. Oak woodland restoration burning is almost identical to seedbed preparation burning. Initially, both methods strive to decrease the stem density of the midstory strata, thereby gently increasing ambient light levels on the forest floor. Both reduce the thickness of the forest floor, creating a favorable seedbed for acorns, and promoting the development of grasses and forbs characteristic of woodlands. Both similarly impact the acorn insect pests that inhabit the forest floor as well as recycle nutrients sequestered in the fine woody debris.

Figure 56.—Prescribed burning to restore open oak woodlands is often done at the landscape scale (top) using aerial ignition (bottom). Photos by Michael Bowden, Ohio Division of Forestry, and Thomas Waldrop, U.S. Forest Service.

Conceptually, there are several important differences between seedbed preparation burning and ecological burning for woodland restoration. First, the sizes of the burn units usually differ. Seedbed preparation burns are done at the stand level or smaller scale by hand (drip torch) ignition while woodland restoration burns are generally implemented at a multi-stand to landscape scale by aerial (helicopter) ignition (Fig. 56). Second, protection of mature oak trees differs. In seedbed preparation burns, protecting mature trees is a high priority because they are the seed source for future seedlings and will be harvested once stocking goals for oak reproduction are satisfied. In woodland restoration burning, tree protection is much less critical (Fig. 57). It is still important for future acorn production, but scarring of mature trees is much less serious because these trees will likely never be harvested or their cutting will be to meet management objectives other than timber production. Once there is sufficient oak reproduction

Figure 57.—In forests managed for timber production, fire damage like that pictured here is unacceptable. However in woodland restoration burning, bole damage is much less critical. Photo by Patrick Brose, U.S. Forest Service.

to meet stocking goals, the two prescribed fire types differ in the implementation of future burns. At this point in seedbed preparation, fire is discontinued. No more burning is done as the stand passes through the oak regeneration process unless necessary, i.e., release burning to control mesophytic hardwood competition. In woodland restoration burning, prescribed fire will continue on a periodic basis. The exact periodicity of future burns depends on local conditions and management objectives and can be quite variable. As established in Chapter 2, the historic mean fire intervals (MFIs) varied among and within regions. Periods of frequent fire were common as were multi-year and multi-decadal fire-free periods. This variability in MFIs is a critical component in oak communities where fire is an important ecological process. Frequent fires are essential when fire has been excluded for too long and to help develop woodland flora and reduced the shrub and tree cover in the mid and understory layers. However, sufficient oak advance reproduction is needed when preparing to replace the overstory, and this may require the establishment of new oak seedlings when sufficient numbers are lacking to meet future overstory stocking goals. Sufficiently long fire-free periods are crucial for the recruitment of the oak regeneration into larger size classes so trees are large enough to withstand future fires and are permitted to continue to growth into the overstory.

Planning for ecological restoration burns in oak woodlands is rather simple and straightforward. The proposed burn unit is delineated by natural and/or man-made boundaries that function as the control and contingency lines. Anderson Fuel Model 09 (AFM-09) adequately portrays the fuel bed characteristics and provides reasonable fire behavior estimates for the vast majority of environmental conditions under which most prescribed burns are conducted in eastern North America (Brose 2009a). The exception to this is when the burn unit has an understory shrub layer of ericaceous (heath) species such as blueberry or mountain laurel. If the heath shrub is a deciduous species such as blueberry, AFM-06 is a good choice for planning purposes. Evergreen heath shrubs like mountain laurel are not well characterized by any of the 13 AFMs, but AFM-05 is a reasonable representation and AFM-10 and AFM-04 will provide a lower and upper bound on what to expect for minimum and maximum fire behavior. Because woodland restoration burning is generally done on a multi-stand basis using aerial ignition, spot-head firing often is the ignition pattern used because this method creates a mosaic of fire intensities from creeping, low-intensity backing fires to running, high-intensity head fires. See Waldrop and Goodrick (2012) for more details on planning and conducting prescribed fires.

Figure 58.—Oak savannas are characterized by widely-spaced trees and a diverse herbaceous community of forbs and grasses. In eastern North America, oak savannas only occupy a small fraction of their historic range. Photo by Daniel Dey, U.S. Forest Service.

Season of burn is very important in woodland restoration burning because other means to reduce midstory stem density are often not employed or are unavailable. Growing season fires should be emphasized at the beginning of restoration because they will cause more mortality to the understory strata than dormant season fires. Once the desired stand structure is achieved, dormant season fires can be used to maintain it. Reduction of overstory density to create open woodlands can be achieved by increasing fire intensity, stem injection with herbicides, or by timber harvesting.

The drawbacks of woodland restoration burning and the mistakes made when implementing it are the same ones detailed for seedbed preparation burning. The most common mistakes are generally made at the beginning of restoration and include not using growing season fires and not burning frequently enough. Both of these result in little substantive change in midstory stem density. Another mistake is using fire too frequently once restoration is achieved, and regeneration to replace the overstory is needed. This prevents successful recruitment of the oak reproduction into large size classes so canopy tree replacement can eventually occur.

Oak Savannas

Savannas are characterized by grass cover with widely-spaced trees (Fig. 58) (Anderson et al. 1999, McPherson 1997, Nelson 2010). The ground flora is a mixture of grasses and forbs common to prairies and woodlands. Scattered patches of shrubs may occur on more fire-protected sites. Tree cover may vary from 5 to 50 percent but must be low enough to permit dominance by grasses and other sun-loving plants. Historically, savannas occurred along the edges of prairies, representing a compositional and structural transition from prairie to woodland and forest. Savannas were prevalent on flat to gently rolling lands of low topographic roughness where fires burned more frequently in the past and retarded the encroachment of trees and shrubs (Batek et al. 1999, Grimm 1983, Stambaugh and Guyette 2008).

Figure 59.—The extended absence of fire allows oak savannas to succeed to closed-canopy forests. Once they have reached this point, they are difficult to restore. Photo by Daniel Dey, U.S. Forest Service.

In North America, savannas were a major terrestrial biome before widespread European settlement. Nuzzo (1986) estimated that about 30 million acres of oak savannas occurred throughout the central United States in 1800, but today <0.02 percent of the original savannas remain. The greatest loss of the original savannas occurred when they were converted to agriculture production. Those that remained rapidly succeeded to forests when fire was suppressed (Fig. 59).

In areas of intermediate rainfall (25 to 50 inches per year), savannas are ecologically unstable and must be maintained by frequent fire (Mayer and Khalyani 2011, Starver et al. 2011). Despite relatively low mature tree density in oak savannas, an abundance of oak seedling sprouts persist in the ground layer of vegetation, and when a sufficient fire-free period occurs, these sprouts grow rapidly and form closed tree canopies in about 20 years (Cottam 1949, Curtis 1959, Nelson 2010). If they are allowed to grow large enough, the trees gain resistance to being killed by subsequent fire.

Restoration of oak savannas entails reducing the density of trees and reintroducing fire (Fig. 60). Most understories of overgrown savannas have 3 to 5 percent of full sunlight, and much more light is needed to stimulate germination, promote growth, and encourage seed production of the herbaceous species commonly found in savannas. For example, for grasses to proliferate, tree canopy cover needs to be <50 percent (Anderson et al. 1999, Mayer and Khalyani 2011, Nelson 2010, Starver et al. 2011). Managing overstory crown cover between 5 to 50 percent influences the development of the ground flora. Tree crown cover below 30 percent is needed to promote grass domination and proliferation of sun-loving forbs commonly found in prairies (Nelson 2010). Higher tree cover begins to favor the abundance and diversity of more shade tolerant forbs characteristic of woodlands as the grasses decrease in dominance. Maintaining tree cover above 50 percent inhibits dominance by graminoids in the ground layer.

Figure 60.—Combining timber harvesting (left) with repeat prescribed burning (right) is the fastest way to restore an oak savanna that has deteriorated due to the extended absence of fire. Photos by Daniel Dey, U.S. Forest Service.

Law et al. (1994) published a chart useful for managing stand density to produce desired crown cover in upland oak savannas depending on overstory tree size and density. For example, if the average d.b.h. of overstory savanna trees is 20 inches, then 17 open-grown trees per acre will provide 50 percent crown cover. If the desired tree crown cover is only 30 percent, then 11 trees per acre that average 20 inches d.b.h. will provide the desired crown cover if the trees are open grown.

Fire by itself is a mediocre means to reduce basal area and stocking and increase understory light (Fig. 61). In a closed-canopy forest, low-intensity surface fires only increase understory light up to about 15 percent of full sunlight by reducing the sapling layer (Lorimer et al. 1994, Motsinger et al. 2010, Ostrom and Loewenstein 2006). Moderate to high intensity fires, especially in the late spring and summer, are capable of killing larger trees as well as increasing the proportion of smaller stems that do not sprout postfire (Brose and Van Lear 1998, Brose et al. 2013b). Killing larger, older trees often leads to complete mortality because they are less likely to sprout after death of the stem than are saplings and pole-sized trees (Dey et al. 1996).

Figure 61.—By itself, prescribed fire will not restore an overcrowded oak savanna. The extended absence of fire has changed fuel loadings and properties and has allowed too many trees to grow large enough to withstand fire. Note the abundance of midstory trees and accompanying dense shade despite several prescribed burns in the past decade. Photo by Daniel Dey, U.S. Forest Service.

Figure 62.—Long-term management of oak savannas has to include occasional fire-free periods of sufficient duration so oak reproduction (left) can gain the necessary size to withstand the surface fires and eventually replace the existing canopy trees (right). Photos by Daniel Dey, U.S. Forest Service.

This can be accomplished at a fine, local scale by placing downed, cured tree tops at the bases of live trees or by broadcast burning when fuel moisture and relative humidity are low and fuels are sufficient to generate high fire temperatures for the duration needed to kill cambial tissue. Managing the reduction of larger trees with fire can be problematic because burning under weather and fuel conditions needed to achieve high-intensity fires is risky from a fire escape and safety standpoint, and fire is indiscriminant in what trees are killed. Generally, other practices such as timber harvesting or chemical/mechanical thinning must be employed with fire to complete the restoration process, especially when fire or other major disturbances have been absent for decades (Fig. 62).

Timber harvesting to reduce the density of large trees is an efficient alternative method of large tree removal and affords a high degree of control of the spatial arrangement and composition of remaining trees. It also provides needed income to pay for other costs of restoration. Mechanical cutting of large diameter trees before burning is an effective way of controlling overstory density. Although larger diameter trees are less likely to sprout, they may produce sprouts after mechanical cutting, however, their sprouts are then vulnerable to being topkilled by a subsequent fire due to their small diameter and thin bark. If large trees are unmerchantable or timber harvesting is not a management option, another effective method is the stem injection of herbicides to reduce tree density and cover of larger trees. When applied correctly, herbicides can kill trees and their root systems completely, preventing them from sprouting. Dead trees can be left standing to fall apart over time, if public safety is not an issue. In the process of decaying, snags can provide critical habitat for a wide variety of wildlife. Methods of mechanically girdling trees are also available for killing larger trees, though they are not as effective as herbicides.

In most cases, reducing tree density in combination with fire produces the fastest improvements in ground flora diversity and dominance on sites not previously degraded by livestock overgrazing and soil erosion. Prescribed burning alone generally produces increases in herbaceous species coverage and richness when trying to restore oak savannas from mature forests conditions, but improvements are most dramatic where the overstory is opened up either by the fire or companion thinning/harvesting operations (Hutchinson 2006, Hutchinson et al.

2005b, Kinkead et al. 2013, Waldrop et al. 2008). Even without fire, positive short-term responses in herbaceous richness and coverage have been achieved by timber harvesting (Kinkead et al. 2013, Zenner et al. 2006). Hardwood and shrub regrowth after stand thinning without fire diminishes gains in herbaceous flora in a few years as shade from woody canopies develop.

In addition to using fire to restore and maintain the woody structure of savanna ecosystems, the restoration of fire as a disturbance that shapes the ground flora community is important. Fire promotes germination and growth of herbaceous plants by: removing litter that acts as a physical barrier to germination and seedling establishment; preparing a receptive seedbed for colonization by wind and animal dispersed seed; breaking chemical and thermal seed dormancy by producing heat and smoke; releasing nutrients tied up in the litter; and increasing light and temperature in the regeneration zone by removing litter and reducing woody structure, which stimulates germination and growth. Fire can be managed to favor dominance of grasses, legumes, or forbs by varying the season, intensity, and frequency (every 1 to 3 years) of prescribed burning (Anderson et al. 1999, Nelson 2010). Simple recommendations cannot be given here because vegetation response to fire is complicated by differences in climate, soils, hydrology, grazing, and overstory interactions. However, spring fires favor grass domination in general while summer burns favor forb diversity (Nelson 2010). Dormant season fires have the least impact on the herbaceous plant community (Hutchinson 2006). Grasses thrive under annual to biennial burns, but shrubs, trees, and vines increase in dominance with longer fire-free periods. Consistent application of prescribed fire tends to create homogeneity in the vegetation community, therefore it is recommended to vary the frequency, intensity, and season of burning when maintaining savanna ecosystems (Nelson 2010).

Prescribed fire planning in oak savanna restoration and maintenance is rather simple and straight-forward. The proposed burn unit is delineated by natural or man-made boundaries that function as the control and contingency lines. At the beginning of the restoration process, if there has been no mechanical reductions of basal area and stocking, Anderson Fuel Model 09 (AFM-09) adequately portrays the fuel bed characteristics and provides reasonable fire behavior estimates for the environmental conditions under which most prescribed burns are conducted in eastern North America (Brose 2009a). Generally, spot-head fires lit via aerial ignition are the firing pattern because the objective is litter and understory strata reduction without causing significant damage to the overstory trees. Flame lengths are generally <2 feet and rates of spread are <5 feet per minute. If the overstory has been reduced by harvesting, then use AFM-06 or AFM-10 to represent the fuel loadings to predict expected fire behavior (Brose 2009a). In restored oak savannas, the grasses and other herbaceous plants strongly influence fire behavior. These are best represented by the grassland fuel models, especially AFM-03 (Grabner et al. 1997, Grabner and Dwyer 2001). See Waldrop and Goodrick (2012) for more details on planning and conducting prescribed fires.

Typically restoration of savannas takes place on a larger landscape, at least on public lands like the Mark Twain National Forest (U.S. Forest Service 2005). The replacement of overstory trees on large-scale restoration projects does not require that the entire area forgo prescribed burning when recruiting to replace overstory trees. Given that overstory trees may live for 150 to over 400 years and that it only takes a relatively few trees per acre to provide the desired tree crown cover in savannas, infrequent recruitment on smaller acreages can be sufficient to maintain

Figure 63.—Scrub oak communities are ecological rarities—a result of edaphic conditions and periodic fires—that have tremendous biodiversity value. Photo by Patrick Brose, U.S. Forest Service.

savanna overstories. By continually permitting recruitment to occur on additional smaller areas, a larger savanna landscape can be sustained in perpetuity. The minimum area needed for recruitment depends on the size of the overall landscape and the length of the management rotation, or average longevity of the overstory trees (i.e., 100, 200 or 300 years).

Eventually, overstory trees need to be replaced because individual trees do not live forever. Post oak is one of the longer lived oak species and individuals may live to be over 400 years old, but even they need to be replaced to sustain oak savannas. Individual tree longevity is shortened when the boles of trees are scarred by fires and wood decay develops, structurally weakening the trees. Recruitment of seedling sprouts and grubs into the overstory requires a sufficiently long fire-free period for trees to grow large enough in size to gain resistance to being topkilled by the next fire. In general, this may require a 20 to 30 year fire-free period depending on tree growth rates and source of reproduction (Johnson et al. 2009, Wakeling et al. 2011). Oak stump sprouts are the fastest growing source of oak reproduction. One of the fastest growing oak species in the uplands is scarlet oak, and its stump sprouts can achieve diameters averaging 3 inches in 10 years when growing in the open (Dey et al. 2008b). White oak, bur oak, and post oak are slower growing species. Increasing overstory density reduces the growth of oak sprouts and lengthens the time needed for them to achieve the bark thickness to become resistant to topkill by fire. These longer fire-free periods are not atypical in fire history records for the period before European settlement (Guyette and Spetich 2003, Guyette et al. 2002, Stambaugh et al. 2006).

Oak Shrublands

These rare habitats occur in distinct locations due to edaphic limitations, often excessively-drained, nutrient-poor soils, and are dominated by shrubs and small trees. One such ecosystem is the scrub oak ecosystem of the central and northern Appalachian Mountains that is found on rocky ridgetops and other xeric environments (Fig. 63). The principal oak species is bear oak, a deciduous shrub or small tree. Mountain laurel, huckleberry, blueberry, and sweet-fern are common associate shrubs. Depending on the degree of edaphic limitation and the time since

Figure 64.—In the extended absence of fire, scrub oak communities can develop too much of a pine component or be invaded by hardwoods such as red maple. Photo by Patrick Brose, U.S. Forest Service.

the last disturbance, stunted chestnut oak, scarlet oak, and pitch pine may be present in limited numbers. This shrub ecosystem is valued for its uniqueness, scarcity, and as wildlife habitat. Of the shrubs, bear oak is especially important because it is the food source for the caterpillars of several rare butterflies and moths as well as a source of hard mast for other wildlife species (Grand and Mello 2004).

Periodic prescribed burning of the oak scrub community is necessary to renew and regenerate the shrubs as they become decadent over time. Fire also prevents the tree species from becoming too large and numerous, thus causing shading and nutrient competition problems for the shrubs (Fig. 64). Depending on the amount of encroachment by tree species, initial restoration burns may be as frequent as 3 to 5 times a decade. Once tree encroachment is controlled, fire frequency can be reduced to 1 or 2 fires a decade. Growing season burns are generally recommended for initial restoration, but they must be employed with caution in this shrub community. Mountain laurel and deciduous heath shrubs are highly flammable at the time of leaf expansion because of volatile oils and resins. Flame lengths that are >20 feet are not uncommon with growing season burns in scrub oak communities (Fig. 65). Depending on safety and containment issues unique for each individual scrub oak burn, dormant season fires may be the wiser choice to lessen the fire intensity problem. The tradeoff is less control of encroaching hardwoods. Appropriate fuel models for planning prescribed fires in scrub oak communities are AFM-05 or AFM-10 for dormant season burns and AFM-06 or AFM-07 for growing season burns. A custom fuel model may also be appropriate because of the presence of mountain laurel which is not well represented by any of the standard 13 fuel models. See Waldrop and Goodrick (2012) for more details on planning and conducting prescribed fires.

Figure 65.—Intense fires are a critical part of the ecology of scrub oak communities. Photo by Jennifer Case, The Nature Conservancy.

EPILOGUE

The role of fire in the upland oak ecosystems of eastern North America is complex. Humans have been starting fires for a myriad of reasons throughout eastern North America since the end of the last ice age. Those fires have helped establish and perpetuate oak forests, savannas, shrublands, and woodlands. Presently, fire is ecologically extinct as an important process, and the upland oak ecosystems are in decline because of this absence of fire. Prescribed fire, when applied correctly along with other forest management practices, can reverse this decline and perpetuate upland oak ecosystems into the future.

ACKNOWLEDGMENTS

The authors are indebted to a multitude of fellow scientists and practicing foresters for numerous conversations over the past few years regarding the fire-oak hypothesis and their insights into its complexities and intricacies. We especially appreciate their encouragement to complete a project that became far more complicated and protracted than we ever imagined. Special thanks are due to our reviewers–Margit Bucher, Stacy Clark, Tara Keyser, Greg Nowacki, Susan Stout, and two anonymous individuals. We appreciate their time and effort to carefully read earlier drafts of this General Technical Report (dubbed "The Behemoth" due to its size) and make detailed comments that helped with clarity and conciseness. Additionally, a special thank you is due Amy Scherzer who tackled the onerous task of providing the technical editing. Finally, we thank the Joint Fire Science Program for funding this project. Without the funding and the input of these individuals, this General Technical Report would still be a concept, not reality.

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APPENDIX 1: COMMON AND SCIENTIFIC NAMES OF THE FLORA AND FAUNA MENTIONED IN THIS REPORT

Common Name	Scientific Name
Flora	
American beech	*Fagus grandifolia*
American chestnut	*Castanea dentata*
bear oak	*Quercus ilicifolia*
blackberry	*Rubus* spp.
black cherry	*Prunus serotina*
black oak	*Quercus velutina*
blueberry	*Vaccinium* spp.
bur oak	*Quercus macrocarpa*
cherrybark oak	*Quercus pagoda*
chestnut oak	*Quercus prinus*
common serviceberry	*Amelanchier arborea*
cucumbertree	*Magnolia acuminate*
dwarf live oak	*Quercus minima*
eastern hemlock	*Tsuga canadensis*
eastern white pine	*Pinus strobus*
flowering dogwood	*Cornus florida*
garlic mustard	*Alliaria petiolata*
hayscented fern	*Dennstaedtia punctilobula*
hickory	*Carya* spp.
huckleberry	*Gaylussacia* spp.
loblolly pine	*Pinus taeda*
longleaf pine	*Pinus palustris*
maple	*Acer* spp.
Mohr oak	*Quercus mohriana*
mountain laurel	*Kalmia latifolia*
northern red oak	*Quercus rubra*
oak	*Quercus* spp.
pignut hickory	*Carya glabra*
pin cherry	*Prunus pensylvanica*
pitch pine	*Pinus rigida*
post oak	*Quercus stellata*
red maple	*Acer rubrum*
red pine	*Pinus resinosa*
runner oak	*Quercus pumila*
sassafras	*Sassafras albidum*
scarlet oak	*Quercus coccinea*
shortleaf pine	*Pinus echinata*
silver maple	*Acer saccharinum*
striped maple	*Acer pensylvanicum*
sugar maple	*Acer saccharum*
sweet birch	*Betula lenta*
sweet fern	*Comptonia peregrina*
Table Mountain pine	*Pinus pungens*
tree-of-heaven	*Ailanthus altissima*
white oak	*Quercus alba*
witch-hazel	*Hamamelis virginiana*
yellow-poplar	*Liriodendron tulipifera*
Fauna	
acorn weevil	*Curculio* spp., *Conotrachelus* spp.
black bear	*Ursus americanus*
blue jay	*Cyanocitta cristata*
cerulean warbler	*Setophaga cerulea*
eastern chipmunk	*Tamias striatus*
gall wasp	*Callirhytis* spp.
gypsy moth	*Lymantria dispar*
orangestriped oakworm	*Anisota senatoria*
red-headed woodpecker	*Melanerpes erythrocephalus*
red-eyed vireo	*Vireo olivaceus*
ruffed grouse	*Bonasa umbellus*
scarlet tanager	*Piranga olivacea*
tree squirrel	*Sciurus* spp.
Valentine moth	*Valentina glandulella*
white-footed deer mouse	*Peromyscus leucopus*
white-tailed deer	*Odocoileus virginianus*
wild turkey	*Meleagris gallopavo*
wood duck	*Aix sponsa*

Brose, Patrick H.; Dey, Daniel C.; Waldrop, Thomas A. 2014. **The fire–oak literature of eastern North America: synthesis and guidelines.** Gen. Tech. Rep. NRS-135. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 98 p.

Guidelines for using prescribed fire to regenerate and restore upland oak forests, woodlands, and savannas in eastern North America were developed by synthesizing the results of more than 100 scientific publications. The first four chapters provide background information on the values of oak ecosystems, eastern fire history, oak's adaptations to fire, and the findings of fire-oak research conducted over the past 50 years. The final chapter synthesizes that background information into guidelines that explain how to use prescribed fire to facilitate oak seedling establishment, release oak reproduction from competing mesophytic hardwoods, and rehabilitate open oak woodlands, oak savannas, and scrub oak communities. A reference section is also provided for readers desiring to delve more deeply into the associations between periodic fire and oak forests, woodlands, and savannas.

KEY WORDS: fire history, fire-oak hypothesis, prescribed fire, Quercus, sustainable forestry

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