A REVIEW OF FIRE AND OAK REGENERATION AND OVERSTORY RECRUITMENT

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Abstract.—Fire has played a prominent role in the history of oak in eastern North America, and it is useful today for promoting oak regeneration where competition with other woody vegetation is a problem and for managing savannas and woodlands. We spent the last century extinguishing wildfire from forests for good reason, but now we must spend some time relearning how to use fire as a tool for sustaining oak-dominated ecosystems. The use of fire to favor oak in forested settings where timber production is a goal is very different from its role in managing savannas and woodlands. Fire as a tool originated in wildlife management and then found application in savanna and woodland restoration. In the past 30 years, there has been increased emphasis on fire in silviculture research and forest management. This paper discusses the use of fire in the context of oak ecology and silviculture with emphasis on promoting oak regeneration and dominance. Highlights include: (1) fire interactions with acorns and oak seedlings, and advance reproduction; (2) fire-induced changes in stand structure and understory and implications for oak regeneration; (3) fire as part of the regeneration prescription; and (4) the role of fire in the process of oak recruitment into the overstory.

The future looks bright
for those unafraid to light,
but who know how to use fire
to get what they desire.
Dey 2008

INTRODUCTION

The history of fire in eastern North America has been brought to public attention (Pyne 1982, Williams 1989, Guyette et al. 2002), and fire's importance in promoting the distribution and dominance of oak species is now widely recognized (Abrams 1992). The lack of fire in modern times is listed as one of the major contributors to the successional replacement of oak by mesophytic hardwood species. These competitors are favored by increasing forest density and disturbances that create small forest openings the size of single to small groups of canopy trees (Nowacki and Abrams 2008).

In the East, fire is beginning to be used to (1) favor oak regeneration in an attempt to sustain oak forests; and (2) restore oak woodlands and savannas. Through research and operational use of fire in eastern forests, we are learning how to use fire to manage oak systems that occur over such a large and varied landscape. This paper reviews some of what we know about fire and oak ecology and silviculture. We discuss how fire may be used to favor oak regeneration and recruitment in forests, woodlands, and savannas. We review key fire effects on oak regeneration from acorn germination to seedling establishment and development. Fire in combination with thinning and regeneration harvesting is discussed in relation to managing stand structure with the goal of sustaining oak beginning with the regeneration process. Following regeneration, oak trees must be successful in competing through stand development to achieve the goal of sustaining oak in the mature overstory, a process we refer to as "recruitment." Together, regeneration and recruitment of oak are essential to sustain oak forests, woodlands, and savannas.

ACORN GERMINATION AND SEEDLING ESTABLISHMENT

Acorn germination in species of the white oak group (*Quercus* section *Quercus*) begins in the fall when the radicle emerges before the seed goes into winter dormancy. White oak germination is completed in the spring with development of the epicotyl. In contrast, red oak group species (*Quercus* section *Lobatae*) have embryo dormancy and require a period of cold stratification before germination in the spring. Regardless of species, acorns must maintain high seed moisture content to remain viable. The white oak group species require moisture content in excess of 40 percent to maintain seed viability (Korstian 1927). Red oak group species can tolerate greater seed drying and viability is good above 25-percent moisture content. In either case, seed desiccation during the winter is a major cause of seed loss in many ecosystems (Korstian 1927).

Acorns fall to the ground in autumn just before or during leaf drop. The covering of leaves helps maintain seed moisture content. In more northern climates, permanent winter snowpack creates an excellent environment for seed storage and stratification. At the ground-snow interface, temperatures and humidity are just right for acorns. Contact with, or burial in, mineral soil provides further protection against seed drying, and buried acorns may be less available to seed predators. Some small mammals and birds are key agents of acorn dispersal and burial, but along with insects and other wildlife species, they also consume much of the annual acorn crop in the process. Hence, seedling establishment is greatest in years of good to bumper acorn crops, when seed predators are overwhelmed with a bountiful seed supply.

Deep litter (> 2 inches) can be a physical barrier to epicotyl emergence from acorns located beneath the litter layer. Furthermore, radicles emerging from acorns lying on or mixed in thick litter over duff layers may be unable to penetrate into mineral soil before they dry out and die. Fire that reduces litter and duff layers to less than 2 inches thick before the autumn acorn and leaf drop favors the establishment of oak seedlings. The benefit of a fire removing litter and duff layers lasts for several years because it takes that long for these layers to reaccumulate. In undisturbed, mature oak-hickory forests of the Missouri Ozarks, Stambaugh and others (2006) estimated that it takes 4 years following a fire for the majority (75 percent) of the litter layer to reaccumulate to preburn levels.

Late autumn and early winter fires that burn after seed drop and leaf fall tend to remove the beneficial covering offered by the current year's leaves, thus promoting seed desiccation over the winter. In addition, the heat from a fire after acorn drop directly kills a high proportion of the seed crop. Auchmoody and Smith (1993) reported that a cool fall prescribed fire in northwestern Pennsylvania killed 40 to 49 percent of the acorns in the litter, and the combination of fire and acorn weevils lowered germination rates by 20 percent compared to unburned acorns. Dey (unpublished data) found that a spring surface fire in an Ontario northern red oak-maple stand reduced acorn germination capacity from 85 to 16 percent. Acorns buried in mineral soil are better able to survive surface fires because (1) they are insulated from the heat of surface fires by soil, which is generally a poor heat conductor when soil moisture is at field capacity or less; (2) low intensity fires, common in the East, are less likely to heat the soil to lethal temperatures; and (3) dormant-season fires occur when ambient temperatures and seed physiological activity are low.

Iverson and Hutchinson (2002) and Iverson and others (2004) measured soil temperatures during spring surface fires in Ohio oak forests and found that the greatest maximum temperature observed at one location was 82 °F at 0.4 inches deep in the soil even though maximum air temperatures 4 inches above the ground ranged from 325 to 600 °F. On average, they found that surface soil temperatures during fires reached only 45 to 51 °F, depending on fire frequency. These soil temperatures were insufficient to cause death to living organisms and plant tissue in the soil, including buried acorns and tree roots. If a good crop of acorns is on the ground, it is best to delay burning until seedlings are established and have grown large enough to respond by sprouting vigorously after burning. This process may take 3 years or more, depending on overstory density (i.e., degree of shading) and site quality (Brose 2008). Mechanical scarification may be an alternative to fire for breaking up deep litter layers and burying acorns. Both Rathfon and others (2008) and Lhotka and Zaczek (2003) found that mechanical scarification increased the density of oak seedlings that established after seed fall.

SEEDLING DEVELOPMENT

Fire damage to a tree's cambium, leading to death of the shoot or the entire individual, is related to temperature and duration of the tree's exposure to fire's heat. In general, plant tissue dies when it is exposed to ≥ 140 °F for 60 seconds (Hare 1965). Longer exposure to lower temperatures can also be lethal. Average maximum temperatures at or near the ground (i.e., within 10 inches) during spring (dormant-season) prescribed fires in hardwood forests have been recorded from 183 °F to 698 °F in the Missouri Ozarks (Dey and Hartman 2005), Ohio (Iverson et al. 2004, Rebbeck et al. 2004, Hutchinson et al. 2005, Phillips et al. 2007) and the southern Appalachian Mountains (Elliott and Vose 2005, Phillips et al. 2007). Clearly, dormant-season burns are capable of causing death or topkill in hardwood and pine seedlings.

In trees of any species, bark thickness is a major determinant of fire resistance (Hengst and Dawson 1994). A tree's fire resistance increases exponentially as bark thickness increases, and stem diameter has been shown to be significantly correlated to tree survival after fire (Loomis 1973, Regelbrugge and Smith 1994, Dey and Hartman 2005). Oak seedlings that are less than 3 years old suffer high mortality (>70 percent) after a single low intensity dormant-season fire (Johnson 1974, Dey and Parker 1996) in part because of thin bark and low root carbohydrate reserves. Further, because germination in oak is hypogeal, location of the acorn at time of germination, i.e., in the litter or buried in soil, determines to a large extent its ability to survive a surface fire (Brose and Van Lear 2004). The multitude of dormant buds located near the root collar, which give oak its great ability to sprout after death of the shoot, are at much higher risk of mortality when the acorn germinates in the litter than when it germinates an inch or two in the soil. Soil protects seedling roots and other tissues from lethal temperatures during dormant-season fires in Midwestern hardwood forests (Iverson and Hutchinson 2002, Boerner 2006).

Prescribed fires typical of those conducted in eastern North America may cause the death or, more commonly, shoot dieback of hardwood stems that are less than 5 inches in diameter (Reich et al. 1990, Waldrop et al. 1992, Barnes and Van Lear 1998, Brose and Van Lear 1998). A single fire is sufficient to kill the shoot in young, small-diameter hardwoods (Dey and Hartman 2005). Most hardwood species, however, respond to this damage by sprouting from surviving root systems, especially larger advance reproduction in the seedling and sapling size classes (Fig. 1). Only new and recent germinants are significantly more subject to complete mortality following low intensity fires regardless of species. Seedlings growing slowly in the dense shade of mature forest (typical on high quality, mesic sites) are vulnerable to fire mortality for a much longer duration than those growing rapidly in more open environments, where they reach fire-resistant sizes sooner. Factors other than tree size also play an important role in determining whether mortality occurs; for instance, fire intensity, seasonality, and frequency; and plant physiological activity (Whelan 1995, Debano et al. 1998, Dey 2002).

A tree's ability to sprout after the death or removal of the shoot increases exponentially with increasing stem diameter up to a threshold diameter, which varies by species (Fig. 1) (Dey 1991). As tree size increases beyond the threshold diameter, sprouting capacity declines (Fig. 2) (Dey et al. 1996a). Declines in sprouting capacity in larger and older trees are probably a function of (1) increased mechanical resistance to bud emergence as bark thickness increases; and (2) physiological senescence in mature and over-mature trees.

For similarly sized trees, mortality after a single fire varies by species, and oak and hickory species are more likely to survive than many of their common competitors, such as sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.), black birch (*Betula lenta* L.), and yellow-poplar (*Liriodendron tulipifera* L.) (Kruger and Reich 1997, Brose and Van Lear 1998). Dey (2002) and Brose and others (2006) classified common eastern species

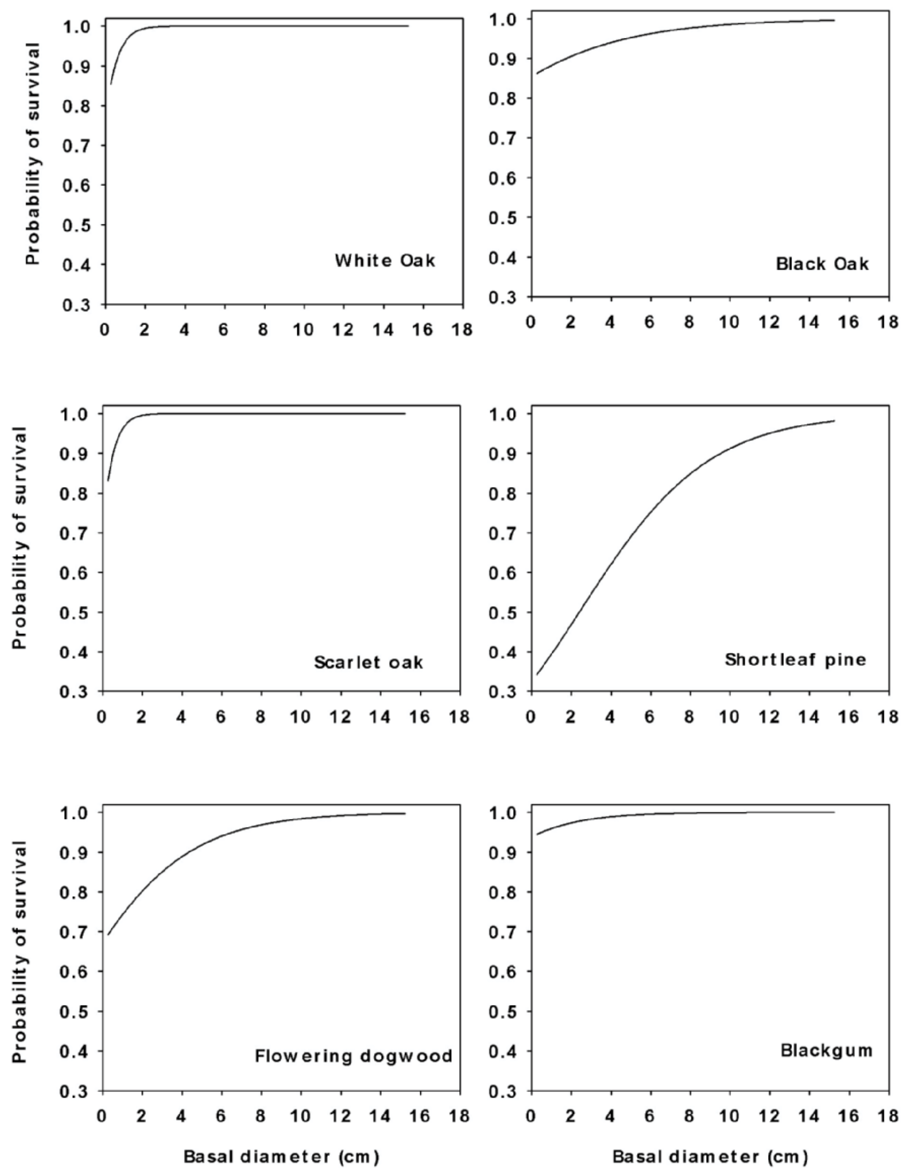

Figure 1.—The probability of advance reproduction's being alive one growing season after a spring (March-April) prescribed burn on The Nature Conservancy's Chilton Creek, MO, property (from Dey and Hartman 2005). Most stems were topkilled by the fire but produced multiple sprouts.

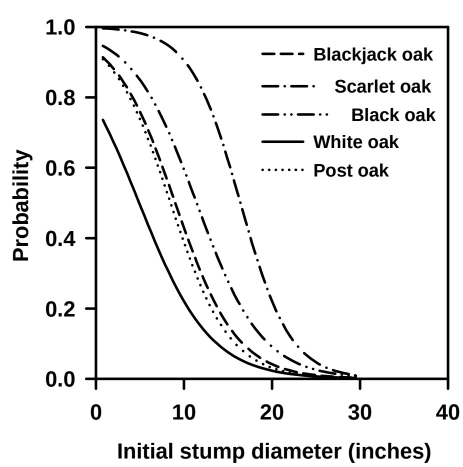

Figure 2.—Estimated probability of having a live stump sprout 5 years after clearcutting, based on initial stump diameter for common oak species in the Missouri Ozarks (from Dey et al. 1996).

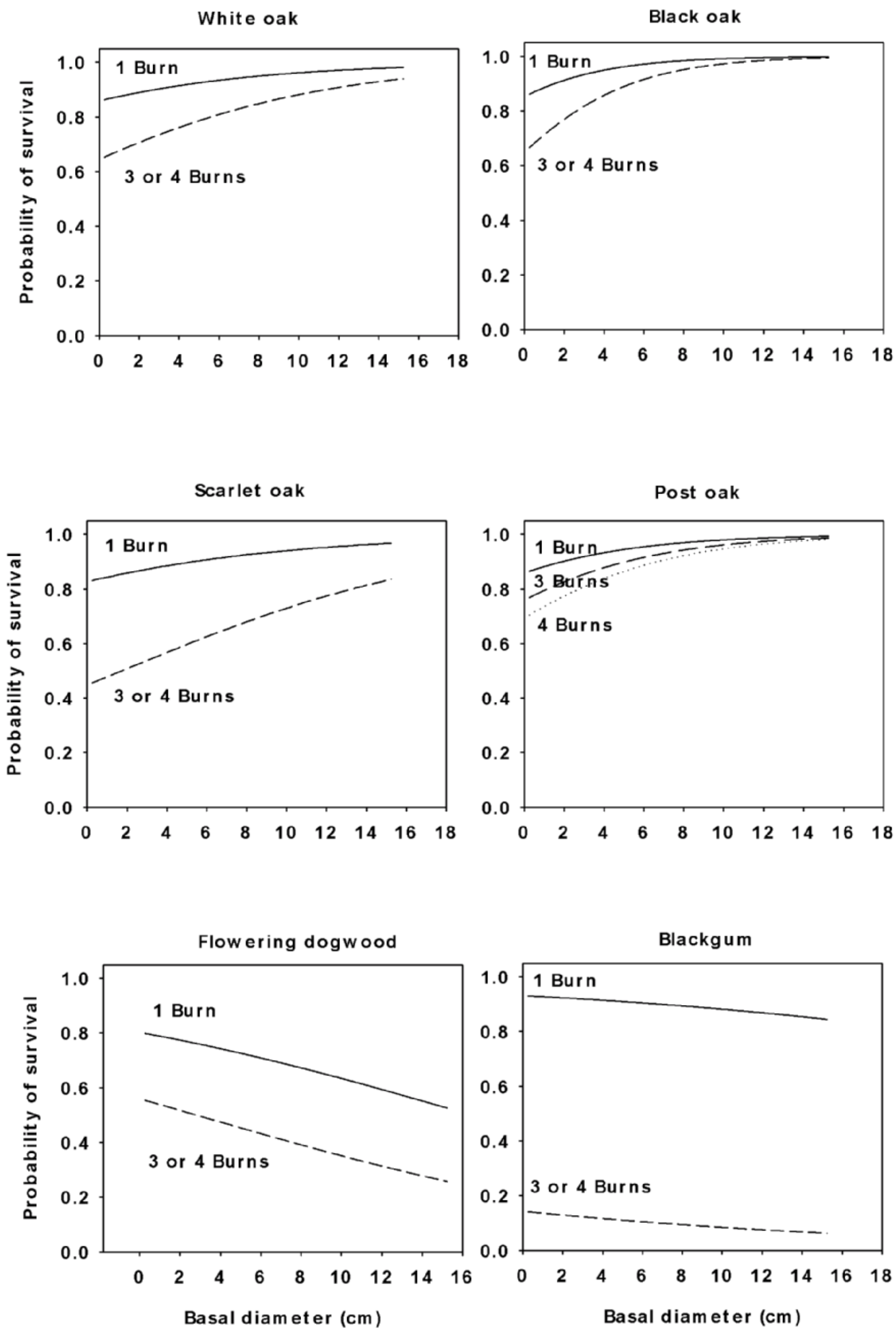

Figure 3.—Probability of advance reproduction's being alive either 4 years after one burn, 2 years after three burns, or 1 year after four annual burns in mature fully stocked Missouri Ozark forests (averaging 78 ft^2/ac basal area and 69 percent stocking) subjected to multiple spring prescribed fires (from Dey and Hartman 2005). Basal diameter of advance reproduction ranged from 0.1 to 6 inches for seedlings and saplings (up to 50 feet tall) before any burning.

Table 1.—Classification of relative ability to survive intact or persist through vegetative reproduction in a disturbance regime of frequent fires for common eastern tree species (from Dey [2002] and Brose et al. [2005]). (* species that are fire-sensitive when young but have greater ability to survive when mature; ** species that are fire-sensitive as older, larger individuals, but are prolific stump or root sprouters).

Very sensitive	Sensitive	Intermediate	Resistant	Very resistant
Balsam fir	American holly	American beech **	Aspen *, **	Bear oak
Eastern redcedar	American Basswood	Cherrybark oak	Black locust **	Blackjack oak *
Hemlock *	American beech **	Blackgum	Black oak	Bluejack oak
Northern white cedar	Aspen *, **	Blackjack oak *	Bur oak	Dwarf chinkapin oak
Red pine *	Black cherry	Nuttall oak	Chestnut oak	Longleaf pine
Virginia pine	Black walnut	Overcup oak	Chinkapin oak	Post oak
White pine *	Cottonwood *	Pin oak	Cottonwood *	Slash pine
White spruce	Elm	Pin cherry	Hickory	Turkey oak
Yellow-poplar *	Flowering dogwood	Red maple **	Northern pin oak	
	Ironwood	Scarlet oak	Northern red oak	
	Laurel oak	Southern red oak	Red pine *	
	Magnolia	Swamp chestnut oak	Sassafras **	
	Red maple **	Swamp white oak	Shortleaf pine	
	Sassafras **	Southern red oak	White oak	
	Silver maple	Swamp chestnut oak	White pine *	
	Striped maple	Swamp white oak	Yellow-poplar *	
	Sugar maple			
	Sweet birch			
	Sweetgum			
	Sycamore			
	Water oak			
	White ash			
	Willow oak			

by their ability to survive as adults or persist through basal stem and root sprouting in a disturbance regime of frequent fires (Table 1). Differences in mortality among species are more significant in the small seedling size classes and are related to ability to regenerate after frequent fire damage. Species differ in morphological and physiological adaptations that protect them from high temperatures during fires, or allow them to regenerate after suffering damage. The type and location of their reproductive structures (dormant buds) and seeds (chemical and thermal seed dormancy and longevity in the forest floor seedbank) determines whether they individually or as a species will survive and persist after fire. Capacity to produce biomass and allocation of carbon within the plant make some species' strategies more competitive than others in a regime of frequent fire. Oaks are survivalists in a world of fire.

One fire seldom causes long-term shifts in species composition (McGee 1979, Wendell and Smith 1986, Van Lear 1991, Van Lear and Waldrop 1991). Only after repeated fires (i.e., annual to every 5 years), whether applied before or after regeneration harvesting, do tree species begin dropping out of mature forest understories, or young stands. Oak reproduction is better adapted than many of its woody competitors because it has numerous dormant buds near the root collar, which is often located buried in the soil, protected from most surface fires. In addition, oak seedlings preferentially allocate carbon to the root system, even at the expense of shoot growth (Kolb and Steiner 1990, Walters et al. 1993). With sufficient light, oak advance reproduction is able to build a large root system with high carbohydrate reserves that supports rapid shoot growth following disturbances causing shoot dieback. This survival strategy is advantageous in environments that are subjected to drought, herbivores that feed on hardwoods, or fire that destroys the shoot. Where large oak advance reproduction accumulate through natural disturbances in "intrinsic oak accumulator systems," i.e., xeric oak forest (Johnson et al. 2002), they often occur in sufficient numbers to sustain oak dominance. In these forests, frequent fire often benefits oak preferentially by improving its competitive status in the regeneration layer (Brose et al. 2006) in part because oak seedlings are large enough to recover from intermittent fire and benefit from the temporary reduction in competition. In "recalcitrant oak accumulator systems," i.e., mesic and hydric forests, oak advance reproduction is unable to persist in the understory and has low capacity to replace the oak in the parent stand. In these forests, small oak seedlings are periodically numerous following a good acorn crop, but shear numbers of small oak reproduction are not enough to ensure success in oak regeneration. Young and small oak advance reproduction have low competitive capacity to regenerate and sustain oak, and they are vulnerable to mortality following intense or frequent fires.

Although frequent fires and high intensity fires may reduce the density of oak seedlings and saplings, oak's relative competiveness is often enhanced by burning because fire's effect on other species is more severe (Brose et al. 2006). The Santee Fire Study in South Carolina (Waldrop et al. 1992) nicely illustrates the tenacity of oaks as they outlasted their competitors after 43 years of frequent burning in summer or winter. In Coastal Plain loblolly pine (*Pinus taeda* L.) forests, it took up to 20 years of annual summer burning to practically eliminate hardwood advance reproduction in the 0- to 1-inch diameter at breast height (d.b.h.) class, and oaks were one of the last species groups to drop out. All woody vegetation less than 4.5 feet tall had been eliminated after 43 years of annual summer burning in these forests, but density of woody species was still high (e.g., 8,000 to 15,000 stems per acre for all species) under periodic or biennial summer or winter burning, and annual winter burning. Allowing 2 to 7 years between fires permitted the hardwood sprouts to continue building root biomass and increase in vigor, especially for the oak species growing under a mixed pine-hardwood overstory. Even with annual winter burning, oak sprouts had an entire growing season to recover from shoot dieback and replenish the supply of root carbohydrates before the next burn. Waldrop and others (1992) predicted that all fire treatments except the annual summer burning would sustain a hardwood midstory that would develop quickly upon cessation of burning, and oak would be a dominant species. Many other studies throughout eastern North America report on oak's persistence and improved competitiveness after long-term frequent burning (e.g., Dey and Hartman 2005).

In recalcitrant oak accumulator systems (Johnson et al. 2002), light levels in the understory are so low (e.g., 1 percent of full sunlight) that oak advance reproduction occurring after a good acorn crop remains small in size, and cohort survival over a 10-year period is typically low, e.g., less than 10 percent (Beck 1970, Loftis 1988, Crow 1992, Parker and Dey 2008). Burning forests with small oak advance reproduction often causes high mortality in oak seedlings and accelerates succession to shade-tolerant species. Shade-tolerant advance reproduction is able to grow to larger sizes in the understory than oak. This ability improves the likelihood that shade-tolerant reproduction will either survive intact or sprout in the shade after a single fire, or infrequent fires. Oak sprouts from surviving root stocks are unable to meet their respiration needs in such low-light environments. Oak species are intolerant to intermediate in shade tolerance, and require 30 to 50 percent of full sunlight for good growth (Phares 1971, Teskey and Shrestha 1985, McGraw et al. 1990, Ashton and Berlyn 1994, Gottschalk 1994, Brose 2008). Therefore, burning in mature, fully stocked stands on high quality sites is usually of little benefit to small oak advance reproduction.

FIRE AND STAND STRUCTURE

Removal of the midstory canopy in mature forests is one way to increase light to small oak advance reproduction. Prescribed burns typical of those conducted in eastern North America are capable of reducing the density of midstory trees (1- to 6-inch d.b.h.) in mature forests (e.g., Waldrop et al. 1992). Midstory density is reduced by fires that kill or topkill trees in that size class. However, density in the smaller size classes often increases dramatically after a fire because many of the hardwood saplings that are topkilled by the fire sprout. Height growth of these hardwood sprouts is slow in the understory of closed-canopy forests because of relatively

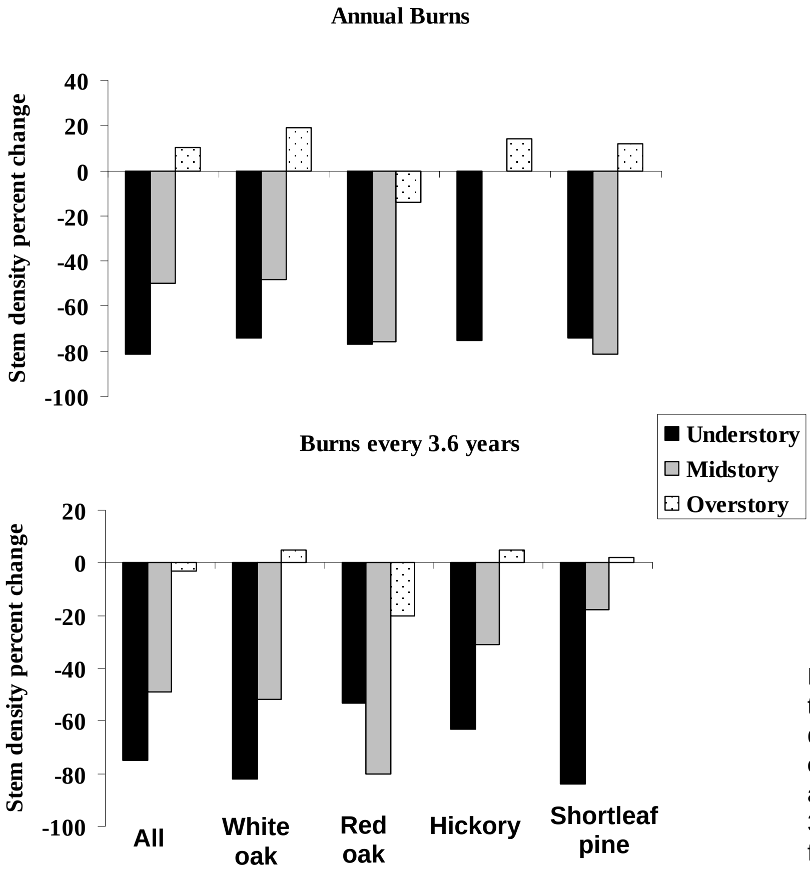

Figure 4.—Percent change in density of trees in the understory (3 feet tall and up to 1.5 inches d.b.h.), midstory (1.5 to < 4.5 inches d.b.h.), and overstory (≥ 4.5 inches d.b.h.) after 10 years of annual spring burns and frequent fires (every 3.6 years on average) in mature oak-hickory forests of the Missouri Ozarks.

low light levels. Four years after a single spring burn in a mature Ozark forest Dey and Hartman (2005) observed that height growth of flowering dogwood (*Cornus florida* L.) and white oak (*Quercus alba* L.) sprouts was slow, and 75 percent or more of the sprouts, some from saplings that were initially as tall as 20 feet or more, were still in the 3-foot height class. Frequent fires over 4 years kept practically all advance reproduction of any species in the smallest height class (1 foot). Thus, one spring fire was effective in reducing the midstory hardwood strata. No doubt understory light levels were increased to somewhere between 10 and 20 percent of full sunlight as has been reported in a number of studies (Lorimer et al. 1994, Miller et al. 2004, Motsinger 2006).

Under the intact closed canopy of the overstory (trees ≥ 4.5 inches d.b.h.), suppression of sprout height growth persists for a number of years, thereby negating the need for annual burning if the objective is to keep understory woody structure low. In mature Missouri Ozark forests, annual or frequent burning (mean fire return interval = 3.6 years) for 10 years did not improve light conditions beyond what was gained from one fire primarily because of its lack of effect on overstory density, i.e., dormant-season fires caused little mortality of overstory trees. However, these frequent spring fires caused 50-percent reductions in the density of midstory trees (i.e., ≥ 1.5 inches to < 4.5 inches d.b.h.) and 75 percent or more in understory trees (i.e., ≥ 3 feet tall and < 1.5 inches d.b.h.) (Figs. 4 and 5). Finally, the effect of surface fires on the midstory varied by oak species. Density reductions in midstory white oak species (40 percent) were half that observed in red oak species (80 percent) after 10 years of burning. In contrast, overstory density was unaffected, or even increased, over the 10 years of frequent burning when spring fires were of low intensity. Moderate to high intensity fires are needed to cause reductions in overstory density through tree mortality. These types of fires may be more appropriate in managing savannas and woodlands across larger landscapes (e.g., thousands of acres), but in forests a more direct and controlled way of managing overstory density and composition is through timber harvesting and stand thinning.

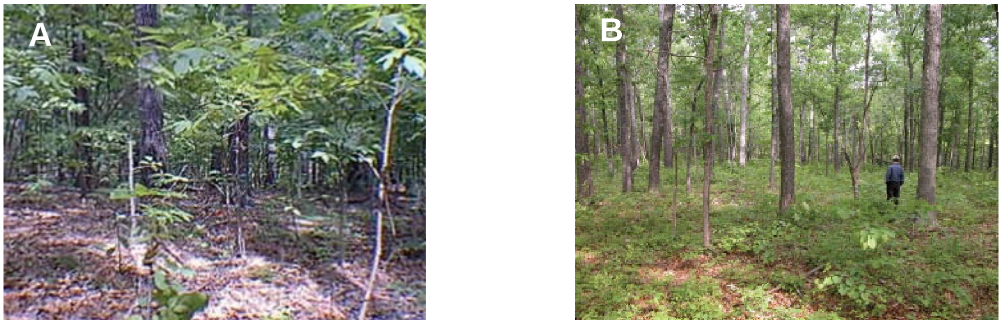

Figure 5.—Low intensity surface fires can alter forest structure in the understory of mature eastern hardwood forests by killing smaller advance reproduction and causing shoot dieback in larger seedlings and saplings. Shown in the photographs is a mature Missouri Ozark forest (A) before prescribed burning and (B) after 10 years of frequent burns averaging one fire every 3 years.

FIRE AND REGENERATION METHODS

Silvicultural prescriptions for regenerating oak should consider combining fire with regeneration methods such as clearcut, shelterwood, seedtree, or group and single-tree selection for managing forest structure to provide a desirable environment for oak reproduction development. Single fires are largely indiscriminant in the species they affect in the smaller size classes. Fire's ability to reduce stand density is stochastic, giving managers less control over species composition, stand structure, and stem distribution within the stand. Prescribed fires are often set in the winter or early spring because (1) burning windows are more common considering weather and fine fuel condition; (2) personnel are less likely to be needed to fight wildfires; and (3) fires are safer to conduct. Dormant-season burning limits the killing power of fire, which may be a plus or minus depending on the outcome managers desire. Fire alone is limited in how big a tree it is able to kill or set back, generally having less effect as tree diameter increases above 5 inches d.b.h.. Fuel loading must be increased or burning done in seasons with high burning indices to increase fire's ability to kill larger trees for reduction of stand density. For these reasons, other methods such as timber harvesting, and thinning by chemical or mechanical practices, are in many cases better suited than fire for managing the density of larger trees (i.e., > 5 inches d.b.h.) and composition of the mature forest overstory.

Light is a major limiting factor in oak regeneration (Abrams 1992, Lorimer 1993, Johnson et al. 2002). Managers control light available to reproduction by managing the various strata of forest vegetation. Reduction of the midstory, whether by mechanical cutting, herbicide application, or prescribed burning, may increase light levels to 10 to 20 percent of full sunlight, which is an improvement over the extremely low light levels (e.g., <5 percent of full sunlight) in mature forests, especially on productive, mesic sites (Lorimer et al. 1994, Barnes and Van Lear 1998, Miller et al. 2004, Motsinger 2006). Survival and growth of oak advance reproduction is improved by this increase in light, but oak reproduction requires 30 to 50 percent of full sunlight to achieve maximum photosynthesis and growth rates (Gottschalk 1987, Hanson et al. 1987, Gottschalk 1994).

Combining fire with one of the regeneration methods is a good way to provide enough light to maximize oak reproduction growth while controlling competing vegetation. Single-tree selection harvesting does not increase understory light much above that in uncut forests and is not often recommended for regenerating oak on mesic sites, or most other places outside of the xeric forests of the Missouri Ozarks (Johnson et al. 2002). A further complication is that fire may scar young trees, which remain for decades to grow to maturity before being harvested. Decay resulting from such scarring takes decades to progress in trees and may cause significant loss of sound volume and declines in tree grade and log quality. Group selection openings of sufficient size (e.g., opening diameter equal to one to two times the height of the dominant trees in adjacent stands) can be used to regenerate oak, but it is hard to apply fire to control competing vegetation within the group openings because the groups are isolated and scattered throughout the stand. Additionally, group selection is often done in combination with single-tree selection harvesting between the group openings.

Fire with clearcutting or shelterwood harvesting probably has the greatest promise for regenerating oaks. Clearcutting to regenerate oak in mixed hardwood forests is most successful when there is adequate regeneration potential from oak advance reproduction and stump sprouts to give some certainty that oak stocking desired at stand maturity will be met. Models for assessing oak regeneration potential based on success probabilities for advance reproduction and stump sprouts are available for some species and regions in eastern North America:

- Loftis (1990a) presented models for estimating performance of northern red oak advance reproduction in southern Appalachian clearcuts
- Loftis (1989), and Schweitzer and others (2004) are developing a regional regeneration model for the southern Appalachian Mountains and Cumberland Plateau
- Dey and others (1996b) developed ACORn for predicting stand size structure and composition for natural regeneration in upland oak-hickory forests in the Missouri Ozarks managed by even-aged methods
- Brose and others (2008) developed SILVAH for regenerating oak forests in the mid-Atlantic Region

Many other reports have been published on oak stump sprouting probabilities (Wendell 1975, Johnson 1977, McGee 1978, Lynch and Bassett 1987, Dey et al. 1996a, Weigel and Peng 2002, Weigel et al. 2006, Dey et al. 2008) and success probabilities for oak planted in shelterwoods and clearcuts (Johnson 1984, Spetich et al. 2002).

When oak advance reproduction is absent, a three-stage shelterwood is a good approach for regenerating and sustaining oak advance reproduction.

1) Fire can be used any number of times before a good acorn crop to begin reducing the density of competing species in the mid- and understory.
2) A light harvesting is done to release the crowns of potential seed-bearing oak trees and to remove the seed producers of competing species, especially species like yellow-poplar.
3) An establishment cutting may be done during a good acorn crop year to increase understory light levels and take the opportunity to manage competing vegetation, but fire should not be used after acorn drop.
4) Once seedlings establish, fire should be withheld until they are large enough to have good sprouting capacity after burning.

If adequate numbers of small oak advance reproduction are already present in the stand, then

1) The initial harvest of a two-stage shelterwood can be used to promote oak seedling growth by increasing the amount of light (Brose et al. 1999a, b).
2) Post-harvest burning may be considered 3 to 5 years later to give oak time to increase in size (e.g., 0.5 to 1.0 inches basal diameter).
3) Monitoring for free-to-grow oak will indicate whether a second burn is needed to control competing woody vegetation. The intent is to get the oak advance reproduction as big as possible before burning.

If fire is undesirable because mortality of small oak would occur, but competing vegetation needs to be reduced, then

1) Mechanical or herbicide control of the midstory and unmerchantable trees can be done in conjunction with shelterwood harvesting. Herbicide application must be done carefully to avoid killing the oak.

2) Higher shelterwood densities are recommended on high quality sites to help retard shade-intolerant competing vegetation (Loftis 1990b, Schlesinger et al. 1993). Yellow-poplar can overwhelm oak reproduction in clearcuts and low density shelterwoods on productive sites.

3) Brose and others (1999b) recommend that oak seedlings be 0.5 to 1.0 inch in basal diameter before burning is considered. Burning may occur at the time of the final shelterwood removal or 3 to 5 years afterwards. Oak does benefit from increased light after removing the shelterwood for a number of years, until crown canopy competition begins limiting light availability to oak.

There is much flexibility in designing a shelterwood prescription that promotes oak by meeting its resource needs while limiting development of competing vegetation. Success requires monitoring and adaptive management. A key ingredient of the regeneration prescription is the management of stand structure to provide adequate light to developing oak reproduction. Although not all oak species are the same in silvical requirements for good growth, most oak reproduction develops more quickly under a shelterwood when light is between 30 and 50 percent of full sunlight. Managers usually underestimate how much of stand stocking must be removed to increase light appreciably in forest understories. Based on a number of studies in widely divergent eastern forest types, 30 to 50 percent of full sunlight requires reducing stand stocking by more than 40 percent, basal area by more than 50 percent, or crown cover by more than 30 percent by harvesting from below and removal of any midstory layer if present (Godman and Tubbs 1973, Sander 1979, Leak and Tubbs 1983, Schlesinger et al. 1993, Schweitzer 2004, Gardiner and Yeiser 2006, Parker and Dey 2008).

Once an adequate density of large oak advance reproduction has developed, final shelterwood removal maximizes oak growth and probabilities of dominance throughout stand development. Retaining overstory trees at some point affects tree growth and eventually species composition of the regeneration. Miller and others (2006) found that clearcutting with reserves, leaving about 23 ft^2/ac in Appalachian mixed hardwood forests, caused 30- to 40-percent reductions in basal area of reproduction compared to similar stands that had been clearcut. They reported that reserve trees suppressed reproduction growth and shifted composition toward more shade-tolerant species. Larsen and others (1997) found that harvesting treatments that left overstory densities greater than 61 ft^2/ac, or 70 percent crown cover reduced oak seedling growth and survival in the Missouri Ozark forests. In the same region, Dey and others (2008) reported that single-tree selection harvesting that left 62 ft^2/ac, or 58 percent crown cover on average significantly reduced the growth of oak stump sprouts compared to those growing in clearcuts. Green (2008) observed decreasing densities of large oak reproduction as overstory basal area increased following regeneration harvesting including clearcutting and single-tree selection. Overstory basal areas above 50 ft^2/ac caused substantial reductions in numbers of large oak reproduction. Furthermore, significant reductions in oak reproduction height growth occurred under only 20 ft^2/ac compared to oaks growing in clearcuts.

Kabrick and others (2008) reported that single-tree selection harvesting in the Missouri Ozarks significantly suppressed the density of oak reproduction (sized ≥ 3.3 feet tall and up to 1.5 inches d.b.h.) compared to clearcutting. Moreover, black oak (*Quercus velutina* Lam.) and scarlet oak (*Quercus coccinea* Muenchh.) regeneration were prominent only in clearcuts. Arthur and others (1998) also noted that openings much larger than multiple tree canopy gaps in oak-pine forests in the Cumberland Plateau were needed for black and scarlet oak regeneration to be successful. They reported that two dormant-season surface fires separated by 2 years and a spring wildfire in mature, ridgetop oak-pine forests resulted in mortality of 16 and 20 percent in the overstory (i.e., trees > 4.0 inches d.b.h.), respectively, causing single-tree and multiple-tree gaps in the canopy. These small to mid-sized gaps were insufficient alone for regeneration of the shade-intolerant oak species.

RECRUITMENT INTO THE OVERSTORY

Regeneration by even-aged methods can be managed to favor oak using prescribed burning to modify competitive relations. Fire can easily topkill stems below 5 inches d.b.h., and repeated fire favors oak species over their competitors. Young stands can be kept in a perpetual state of stand initiation with frequent fire. Eventually, however, fire must be withheld for forest development to proceed if the goal is a mature forest. Once stands reach crown closure, it is probably preferable to manage oaks and competing species by mechanical or chemical stand thinning rather than prescribed fire. To promote recruitment of oak into the overstory, oaks should be initially free to grow, unencumbered by overly dense residual overstories. Fire-free periods are needed to allow for oak trees to grow beyond the sapling size class and develop enough diameter, bark thickness, and height to increase the probability that they can avoid shoot dieback if a fire should occur again.

In Missouri, the average diameter growth for codominant white oak saplings (1 to 3 inches d.b.h.) is 1.5 inches in 10 years (Shifley and Smith 1982). Therefore, a 33-year fire-free period is needed to allow such a white oak to grow to 5 inches d.b.h. and have a better chance of surviving a fire intact. Shifley and Smith (1982) found that average growth rates for red oak species were similar. An important point to note is that half of the trees in their analyses grew at rates greater than the average, assuming a normal distribution in oak diameter growth, and the upper 5 percent of oak trees had significantly greater diameter growth, which would lessen the time needed to develop thicker bark and greater fire resistance. It then becomes a matter of having sufficient numbers of large, fire-resistant oak to meet management goals for oak stocking at maturity.

The fire-free period may not need to be so long for oak stump sprouts, which exhibit an accelerated growth rate for some time after initial sprouting. Dey and others (2008) reported that oak stump sprouts in Missouri Ozark clearcuts grew to an average of 3.1 inches for scarlet oak, 2.3 inches for black oak, and 2.2 inches for white oak in 10 years. If the objective is to use fire to regenerate oak-dominated forests, then once the oaks are free to grow, burning does not have to be considered again until the period when the forest manager needs to create advance oak reproduction for the next rotation, which could be two to three decades before the final regeneration harvest. In woodland or savanna management, periodic recruitment of oak is necessary to sustain the desired overstory density. Because trees of white oak species may live to be 250 to 400 years old, and 80 to 200 years old for red oak species, oak recruitment need only occur occasionally in savannas and woodlands. However, when it is needed, there must be a sufficient fire-free period.

Newly regenerated hardwood stands in eastern North America have thousands of trees per acre, but stand density rapidly declines with time, especially after crown closure (Miller et al. 2007). The oaks that express dominance early have the best, or only, chance of surviving to have a place of prominence in the upper canopy crown classes at maturity (Ward and Stephens 1994). Competition is severe on high quality sites, and oaks have little chance of maintaining dominance without some type of management intervention (Hilt 1985), such as crop-tree thinning applied when the stand reaches crown closure (Miller et al. 2007).

FINAL THOUGHTS

Efforts to use fire to sustain oak-dominated forests, and to restore oak woodlands and savannas, have increased over the past 20 years, especially in the Great Plains-Eastern Forest ecotone. Historically, fire promoted the invasion of prairies into eastern forests as far as Ohio, creating the Prairie Peninsula Region (Transeau 1935). During this time, Native Americans had a great effect on the distribution of forest and prairie in the East through their use of fire. An eyewitness account by Black Hawk, a Sauk warrior in the early 1800s, testifies to this influence. In 1832, Black Hawk led his people in a fight to secure their homeland in northern Illinois and southern Wisconsin from settlement by frontiersmen and their families. Defeated in battle, Black Hawk and a small group of chiefs and leaders were transported east to meet with President Andrew Jackson. They were taken on a tour through Philadelphia, Baltimore, and New York

City to impress upon them the strength of the United States and the futility of further fight with the invading European settlers. In New York the Indian delegation viewed a fireworks display, of which Black Hawk noted in his autobiography originally published in 1833:

> *The chiefs* [U.S. military and political leaders] *were particular in showing us every thing that they thought would be pleasing or gratifying to us. We went with them to Castle-Garden to see the fireworks, which was quite an agreeable entertainment–but…less magnificent than the sight of one of our large prairies would be when on fire.*

Fire was not merely an entertainment spectacle for the Indians; they used it to manage their lands to provide for the needs of the people. The Sauk and neighboring tribes used fire to cultivate large (e.g., 800-acre) crop fields of corn and other vegetables and manage native prairies as pastures for their horses and wild game (Black Hawk 1833).

In modern times in the East, fire is still largely an anthropogenic phenomenon, but we suppress fires before they burn much land, and this action has greatly altered the fire regimes promulgated by the Native Americans. The ill effects of fire on forests from a timber perspective and the shadow of Smokey Bear still have a strong influence on the use of fire in forest management. Today, our understanding is improving in how fire:

1) acts on plants through biological processes,
2) modifies a species' regeneration and development through ecological processes,
3) changes the competitive relations among species, and
4) affects long-term site productivity and ecosystem integrity by modifying physical properties and biological components of the site.

We are quickly moving away from the simple approach of "return frequent fire to the system and all will be well." We are moving toward a more realistic and holistic management system approach by combining prescribed fire with other silvicultural practices to manage forest regeneration and succession within an ecological classification system to achieve well defined objectives desired by society. As in the past, the ecosystem goods and services we desire today guide the role of fire in forest plans and silvicultural prescriptions. Through research, monitoring, and adaptive management, we are exploring new ways to use fire judiciously in managing oak forests for a multitude of benefits including timber production.

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